SEDIMENTATION IN A ROCK-WALLED INLET, LYTTELTON HARBOUR, NEW ZEALAND

A thesis

submitted in fulfilment of the requirements

for the Degree

of

Doctor of Philosophy in Geography

in the

University of Canterbury

by

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University of Canterbury

1985

FRONTISPIECE. An oblique aerial view looking down Lyttelton Harbour. Banks Peninsula is to the left. Photograph by Mannering and Associates Ltd, Christchurch.

ABSTRACT

The principal concern of this study is the examination of sedimentation and sedimentary processes in a rock-walled tidal inlet, Lyttelton Harbour. The harbour is distinctive from other forms of inlets commonly discussed in the literature due primarily to a negligible freshwater input, lateral grain size contours which are parallel to current flow paths, and a maintenance, channel dredging programme which greatly exceeds the natural harbour sedimentation rates. A further unusual characteristic of the harbour is the lateral limitation imposed on processes within the harbour by the surrounding rigid, rock boundaries. These boundaries influence and control circulation patterns within the harbour through the interaction between processes and geometry. Thus Lyttelton Harbour is a structurally controlled tidal inlet. The only harbour boundary which is free to respond to changes in the system is the bed. For these reasons traditional inlet concepts, applicable to estuaries and inlets with unconsolidated boundaries, were found to be unsatisfactory for explaining how Lyttelton Harbour operates.

The study approach involves fieldwork and analysis of both sedimentary and hydraulic processes within the harbour. A bed sediment survey showed that the harbour can be divided along its longitudinal axis with very fine mud sediments on the northern side, and coarser, sandier sediments on the southern side. All bed sediments are predominantly fine, and a survey of near-bed suspended sediment concentrations revealed fluid mud layers on the northern side of the harbour, at the harbour entrance, and within the channel.

The primary hydraulic processes operating are tidal currents, although a mixed wave field, comprising ocean swell and locally generated wind waves, frequently penetrates the harbour. Tidal current velocities are on average around 0.22 ms^{-1}, with flood tide velocities stronger on the south side of the harbour and ebb tide velocities stronger on the north side, inducing a clockwise circulation pattern.

External factors are an important component in the tidal driving forces, comprising coastal weather patterns and a continental shelf edge wave oscillation effect with a period of 2.5 - 3.5 hours. These external influences are the main cause of the duration of both ebb and flood tides varying from 5.0 to 8.25 hours. Interaction between tidal currents and the harbour geometry induces a large gyre in the outer harbour which varies in duration from being absent to operating for up to 50% of any given tidal cycle.

The transport of sand sized material is bidirectional along the harbour length, with erosion of sandy sediments in the centre of the harbour, and deposition at the head of the harbour and at the harbour entrance. Fine muddy sediments are transported predominantly towards the harbour entrance and accumulate in the channel, on the northern side, and in the entrance, forming fluid mud layers. The most concentrated fluid mud regions coincide with the rotatory currents at both ends of the tidal gyre, where sediment is deposited from weaker currents. Transport of sand across the harbour is not apparent, although lateral movement of fine, suspended particles occurs by advection and diffusion in response to the sediment flux differentials and flux gradients within the harbour. This movement of fines results in the lateral gradation of grain size, from coarse to fine, across the harbour from south to north.

The major sedimentary process within the harbour is the maintenance dredging programme which removes up to 1,000,000 tonnes of sediment annually from the channel and port berthage areas. The dredge spoil is subsequently dumped within the harbour along the northern perimeter, although a temporal analysis of dump sites indicated that once a site capacity has been attained, all the spoil dumped at that location is rapidly removed. Sediment input from other sources, primarily erosion of the catchment, has been estimated at less than 45,000 tonnes per annum, substantially less than the channel siltation rate, and the recirculation of dredge spoil was identified as the primary source of sediment causing channel siltation.

Two processes induce spoil recirculation. Firstly the tidal gyre, and secondly the dynamic trap. The dynamic trap system provides a mechanism for the transport of fine grained sediments to regions of high sediment flux, and for the deposition of fine grained sediments under current regimes having both a high competence and a high capacity. The system provides an explanation for the lateral grain size gradation within the harbour, the maintenance of dredge spoil mounds at dump sites, the insensitivity of channel siltation rates to the location of spoil dumping sites around the harbour, and the quasi-equilibrium state of the harbour in spite of the extensive dredging operations. Little sediment is able to escape from the harbour to the open sea due to the flux gradients at the entrance, and the dynamic trap principles. Thus the long term stability of Lyttelton Harbour is maintained, under both natural and dredging conditions, by the redistribution of available sediment within the harbour as a function of internal harbour dynamics.

Throughout the thesis the dynamics of Lyttelton Harbour are compared to existing inlet concepts and theories in order to identify those areas in which this type of inlet is significantly different and where other, poorly understood inlets may be comparable to Lyttelton. Finally, Lyttelton Harbour is defined and classified and a set of principles pertaining to this type of inlet are proposed.

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ACKNOWLEDGEMENTS

I wish to express my sincere thanks to the many people and organisations who helped to make this study possible. In particular, I wish to thank my supervisor, Dr. Bob Kirk, for his advice and guidance with the thesis, and for the time he has given to our many long discussions during the past few years.

I also wish to thank the Lyttelton Harbour Board who provided the financial and logistic support without which the study would not have been possible. Many thanks must go to the launch drivers, divers, engineers, and the many people on the Harbour Board staff who helped by providing equipment, assistance in the field, and information and suggestions about the harbour and the study.

Glen Lauder, Laurie Brown, and Mark Siemelink all helped with an important aspect of my fieldwork by spending a tiresome day at the edge of the harbour watching the tide go out and come in again. My thanks to them for their patience.

I wish to acknowledge Dr. Ian Owens, his library, and his calculator. They all provided very useful suggestions and information for the thesis. Drs. Lionel Carter and Dick Pickrill of the N.Z. Oceanographic Institute also provided some helpful comments on the study.

My thanks to the technical staff in the Geography Department for their invaluable assistance with field equipment, draughting and computing, and also to Mrs. Glenys Lamb for a superb job with the typing.

Finally, I especially wish to thank my wife Nicola, for proof reading the thesis, and for her constant support and encouragement throughout the past 3½ years. Couldn't have done it without you.

ONE

INTRODUCTION

This study concerns sedimentation and sedimentary processes in a rock-walled coastal inlet. Lyttelton Harbour is a volcanically formed tidal inlet comprising a structure of hard rock walls and a single mobile boundary at the bed. The harbour contains the Port of Lyttelton which serves the largest South Island city, Christchurch, and is situated approximately 9 km from the harbour entrance. Figure 1.1 and the frontispiece show the location of the harbour and the port. Access to the port for shipping is via a dredged channel which is maintained by an extensive, ongoing dredging programme.

Lyttelton Harbour can be seen to "differ" from most coastal inlets in a number of important respects. The harbour is notable for a negligible freshwater input, very fine mud sediments, and exposure to a wave field of effectively unlimited fetch. Siltation rates in the dredged channel are far in excess of the natural sediment input from either littoral drift or fluvial sediments, and are thought to result largely from the redistribution of dredge spoil dumped within the harbour. Bushell and Teear (1975) speculated on probable transport mechanisms of the harbour sediments and the source of sediments entering the channel, but undertook no detailed analysis of these processes. However, it is interesting to note their comment (p.66) on 'stability' and sedimentation in the harbour:

> Prior to the period of extensive dredging and dumping in the outer harbour the bed of the harbour appears to have been in approximate equilibrium. Over the period from 1849 to 1951 no significant increase or decrease in the volume of harbour sediments is apparent. The equilibrium is a dynamic form of equilibrium in that where the equilibrium bed levels are altered the system operates to restore the equilibrium levels. Despite the relative stability of the natural bed levels, indicating perhaps small quantities of sediment in motion, the sediment charge of the system is considerable as is evidenced by the channel siltation. The dredged channel is an example of the equilibrium depth being exceeded. In the case of the dredge dumpings...the system operates to increase the depth back to its former equilibrium level.

This statement raises several points of considerable scientific interest with respect to how the harbour functions and how it responds to change. The implications are, that prior to "extensive" dredging the harbour was in a state of equilibrium, and then following the introduction of dredging operations the harbour has reached another, different, state of equilibrium with "relatively stable natural bed levels indicating small quantities of sediment in motion". Thus two separate phases of harbour equilibrium have been inferred; a historical one when the harbour was in a natural state; and a modern one with the harbour substantially altered by the dredged channel, dumping of spoil, and to a lesser degree by features such as the construction of moles and breakwaters at the port. Furthermore, while Bushell and Teear (1975) proposed stable bed levels they also suggest the sediment charge of the harbour "is considerable as evidenced by channel siltation". An implication which can be taken from this observation, and that harbour sediment volumes were unchanged between 1849 and 1951, is that large quantities of sediment, presumably spoil, are being transported out to sea although this was not determined by Bushell and Teear. It is interesting to note that the Lyttelton Harbour Board's dredging records show little change in equilibrium conditions since dredging began, despite the utilization of seven major dump sites at different locations around the harbour during this period.

The existence of the two separate 'states of equilibrium' has not been demonstrated categorically. If it can be shown that they do exist, then several important questions arise:

(1) What factors controlled harbour stability under natural conditions, in an inlet possessing only one mobile boundary which can be subjected to alteration to achieve stability?

(2) In what manner did the harbour respond to substantial changes to the system, in the form of the channel, which upset the equilibrium?

(3) What factors currently control harbour stability under the new conditions, with the channel dredged and spoil dumped within the harbour?

The purposes of this thesis therefore, are to examine the hydrodynamics and sedimentation of Lyttelton Harbour and to investigate the nature of the harbour stability in order to determine the factors which control the harbour dynamics and equilibrium conditions. As indicated in the foregoing discussion, the main factors which appear to be pertinent to the study, such as dredging operations and boundary mobility, are internal to the harbour.

A major problem with approaching a study of this sort is that the mechanics of physical processes operating within tidal inlets, as opposed to those at the entrance, have been little studied and are poorly understood. In particular, there is a conspicuous dearth of literature examining hydraulic and sedimentary processes within "rigid boundary" inlets such as Lyttelton, and the interactive effects between these processes and a hard rock geometry. Analysis and determination of the factors which influence the physical processes and control the stability of Lyttelton Harbour will therefore provide a significant contribution to the broader scientific knowledge relating to tidal inlets in general.

1.1 STUDY APPLICATIONS

1.1.1 Applied Aspects

Lyttelton is New Zealand's deepest draught and berthage port due to the large scale maintenance dredging operation which began in 1876 (Scotter, 1968). The existing schedule maintains a 7 km channel at approximately 12 m depth, mean low water spring tide (MLWS), shown in Figure 1.1, and requires the removal of 700,000 to 1,500,000 tonnes of sediment per annum from both channel and berthage areas. While a small percentage of this quantity has been dumped at sea or utilized in reclamation, most of the spoil has been dumped within the harbour along the southern and northern sides: at Camp Bay (Fig.1.1) prior to 1904, at Camp Bay and Little Port Cooper between 1904 and 1949, and then additionally in Gollans Bay up until 1969. Since 1969 dumping has been primarily along the northern side of the harbour at Livingston, Breeze, and Mechanics Bays and at White Patch Point.

Two main reasons exist for dumping spoil within the harbour. Firstly, any dredging policy ideally establishes an optimum between the two extremes of continuous dredging and dumping directly over the side, whereby maximum quantities of sediment are both removed and recycled, or achieving minimal dreding but dumping at sea so that minimal spoil recycling occurs. Primary factors involved in decision making in dredging are the ability to maintain the desired channel depth, and the cost of operating the dredge. Dumping spoil along the edges of the harbour is the policy adopted by the Lyttelton Harbour Board.

The second reason, and the major reason for transferring dump grounds from the southern to the northern side of the harbour, reflects an attempt to regulate the wave environment within the harbour. Bushell and Teear (1975) report that spoil mounds are formed on the sea bed on the northern side to induce wave refraction and reduce wave energy. They found evidence for "...a significant wave energy reduction in the harbour due both to the effects of selective dumping, ...and due to the extension of the channel".

To date the transport of spoil from the dump sites and its resultant deposition have not been ascertained, so that the 'validity' of the reasons for dumping spoil within the harbour has not been established. Furthermore, since spoil is likely to comprise a major proportion of the sediment available for transport within the harbour, knowledge of the manner in which it accumulates or is redistributed will provide a better understanding of the factors controlling sedimentation and stability. For these reasons, the applied aspects of the study focus specifically on establishing the immediate source of sediments entering the channel, the transport mechanisms and directions of spoil from the dumping sites, and the effects of dredging, in particular spoil mounds, on the harbour dynamics and stability.

An additional aim of the applied side of the study is to assess the possibility of a reduction in dredging operations. Although a large degree of interaction between physical processes and dredging is predicted here, earlier studies of the hydrodynamics and sedimentation in Lyttelton by Brodie (1955), Garner and Ridgway (1955), and Heath (1975), have ignored the effects of spoil, save to indicate that it increased the rate of shoaling of the harbour bed (Brodie, 1955). Any knowledge of the interrelationships between processes and dredging gained from this study should provide considerable insight into management criteria not only for Lyttelton, but for similar types of inlets and harbour dredging operations in general.

1.1.2 Application to Inlet and Estuarine Sedimentation

Examination of tidal inlet literature reveals that most work undertaken has concentrated on hydraulic processes. Thus Krause and Ohm (1984; p.611) observe that;

> Net transports of seston, occurrence of turbidity clouds and mud deposition are phenomena which are not properly understood scientifically, and the necessary dredging of shipping channels through estuaries poses numerous practical and financial problems.

This lack of knowledge of estuarine sedimentary processes results from the considerable emphasis researchers have placed on estuarine circulation patterns. Typically, estuarine studies have analysed the salinity structure throughout an inlet which reflects the degree of vertical mixing in the water column, and this analysis leads almost by implication to the circulation pattern in the inlet. Numerous papers exist examining circulation and hydrology in estuaries (e.g. Arons and Stommel, 1951; Bowden, 1960, 1967, 1977; Dyer, 1977; Garvine, 1977; Hansen and Rattray, 1965; Haas, 1977; Officer, 1977; Pritchard, 1955, 1967a; Rattray, 1977; and many others). Fewer studies include work on sedimentation in estuaries, and where it is included sedimentation tends to be analysed in terms of the estuarine circulation patterns rather than the actual mechanisms involved in the sedimentation process. A resultant feature of estuarine circulation is the "turbidity maximum" (Section 2.2) which Allen et al. (1976) consider "...controls the sedimentation of suspended sediment in estuaries...". Dyer (1979; p.11) states that "...the estuarine circulation pattern is important in determining the sediment movement". However, in one type of estuary classified by Pritchard (1952) as "well mixed" and having no vertical salinity structure, Allen et al. (1980) and Castaing and Allen (1981) have recently indicated that tidal processes may be more important than "estuarine" processes in transporting fine sediments. In these inlets, applying estuarine concepts such as turbidity maxima to infer sedimentation patterns, as suggested by Dyer (1979) and done by Inglis and Allen (1957), would therefore appear to be rather tenuous.

Nowhere are hydraulic and sedimentary processes less understood than in well mixed estuaries. In this context it is interesting to consider classifications of inlets and estuaries proposed by Caldwell (1955), Heath (1976b), and Pritchard (1952, 1955) (discussed in Section 2.1). In all cases they group inlets by a set of basic principles based on physical parameters of the inlets and from these, general principles are derived for dynamics and circulation patterns to be applied to other inlets with similar physical parameters. Thus by the very nature of the classification systems, processes operating within inlets, particularly with respect to sedimentation, tend to be inferred from other physical parameters rather than being determined from actual measurements. In Section 4.1 it is demonstrated that Lyttelton Harbour is not an estuary, and yet it will also be demonstrated in the ensuing chapters that many of the characteristics applicable to the description of well mixed estuaries are also applicable to the description of Lyttelton; such as lateral circulation and tidal mixing. However, concepts which have been developed in the literature to describe inlets and estuaries are unsatisfactory by themselves for explaining those features of Lyttelton mentioned at the outset of this chapter and which make it "different".

It should be reiterated here that a particular aspect of Lyttelton which makes it different from most non-estuarine tidal inlets examined in the literature is its solitary mobile boundary at the bed. Most tidal inlets studied have multiple mobile boundaries, and because the commercial viability of inlets is dependent on entrances remaining 'large' enough to accommodate shipping, most studies of non-estuarine inlets have focused on entrance characteristics (e.g. Bruun, 1966, 1978; O'Brien, 1931, 1980). Little emphasis has been placed on determining the mechanics of sedimentation within inlets, and more particularly, on assessing the effects of internal processes on inlet stability.

Thus, while this study will utilize many principles and techniques which already exist in the literature germane to inlets and estuaries, it is anticipated that the determination of the factors which control the internal dynamics, and stability of Lyttelton Harbour, will generate new concepts with application to less studied and poorly understood processes such as the internal stability of non-estuarine inlets, or stability and sedimentation in well mixed estuaries. Furthermore, the derivation of new principles to explain the "differences" of Lyttelton will require the harbour to be defined and classified in terms of these principles. It may well be found that other types of inlets which do not readily fit existing classifications may be more easily described by principles which describe the dynamics of Lyttelton.

1.2 NATURE OF THE STUDY AREA

Lyttelton Harbour is located on the northern side of Banks Peninsula, on the east coast of the South Island, New Zealand (see Figure 1.1). Banks Peninsula comprises two volcanic cones, Akaroa, and Lyttelton which is the smaller of the two. Lyttelton Harbour developed as a result of stream erosion of the central area of the cone, and subsequent drowning of the valley by the sea formed an erosion caldera (Speight, 1917). The caldera rim is generally 300-450 m above sea level with the highest point being 700 m. Reconstruction by Liggett and Gregg (1965) puts the original height of the cone at between 1650 and 3000 m, indicative of substantial erosion which has occurred over time. The consequence of such development is that the perimeter of the harbour comprises predominantly sheer rock cliffs which

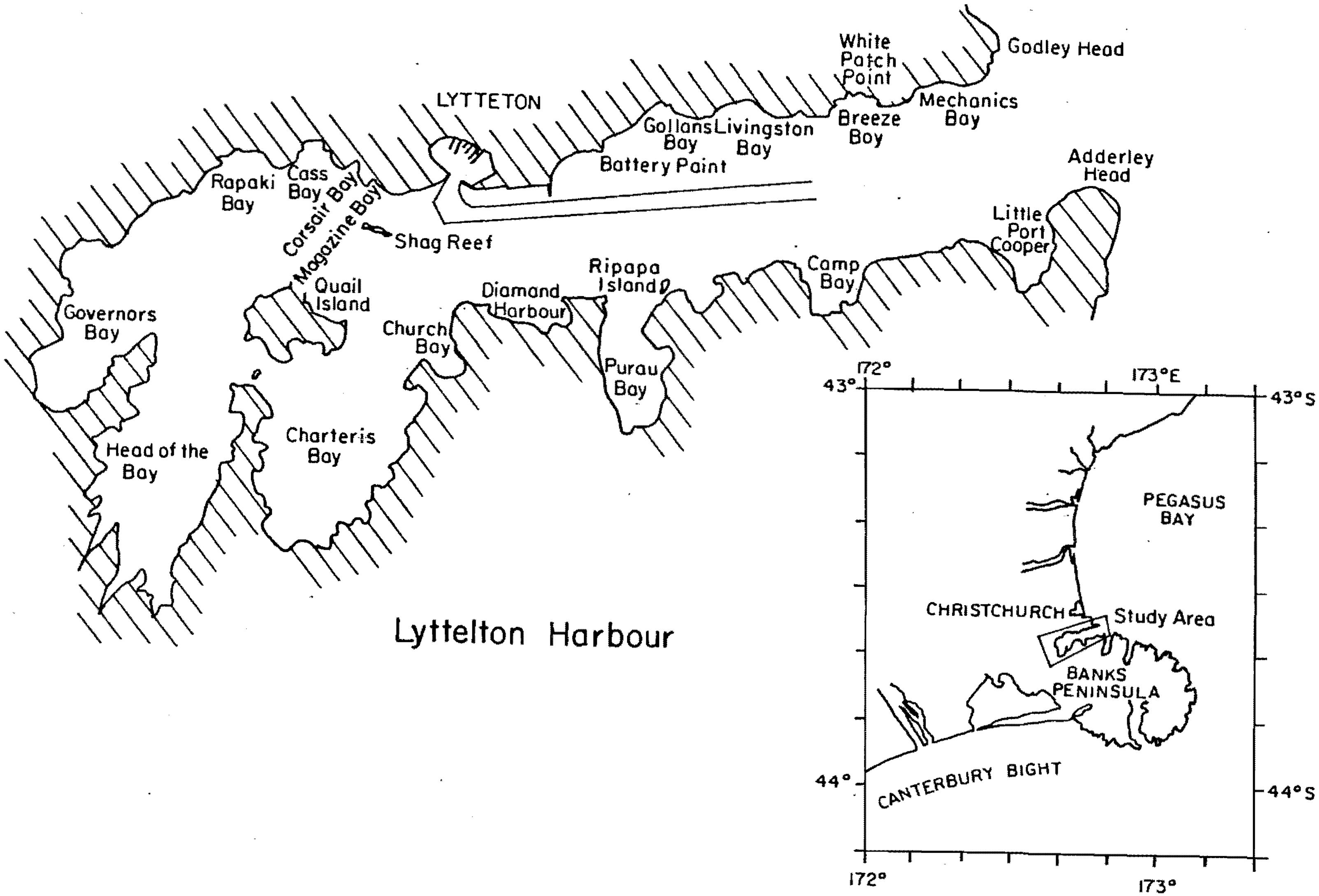


Figure 1.1 Location of study area.

descend to a flat sea bed and form a virtually rectangular cross-section.

The main rock structure comprises andesite, basalt, rhyolite, pitchstone, trachyte and minor tephras from several volcanic phases in the Miocene. The geology of the area is presented in detail by Liggett and Gregg (1965) and Speight (1917; 1944). Of more significance to this study are thick layers of aeolian loess on the lower catchment slopes, transported from the Canterbury Plains during the later Pleistocene (Raeside, 1964). These deposits reach depths of 10 m in areas at the head of the harbour, and are generally regarded as the source of silt which has infilled the harbour basin to depths up to 47 m (Bushell and Teear, 1975). Catchment erosion and basin infilling has created extensive tidal flats at the head of the harbour in Governors Bay, Head of the Bay, and Charteris Bay, which cover an area of approximately 11 km^2 at MLWS. These three bays carry the main fluvial inputs into the harbour from the catchment, although fresh water discharge is minimal. Speight (1917; p.367) observes that "...catchment valleys are short, and streams are diminutive torrents which fail altogether or carry but little water in dry weather".

The harbour is 14 km in length with an average width of 2 km, except at the head where it expands into the broad expanse of tidal flats in the three bays which are separated by peninsulas and by Quail Island. The sea bed is to all intents and purposes flat, with a gentle gradient of 1 in 1000 extending from the tidal flats to a depth of 15.5 m below mean sea level (MSL), at the harbour entrance. Orientation of the harbour is in an ENE-WSW direction, with the entrance being exposed to an unlimited wave and swell fetch to the ENE. Dominant wind directions are from the north-east and south-west (McKendry, 1985), with the high cliffs tending to funnel the flow along the length of the harbour. This, combined with the limitless wave fetch at the entrance, provides the potential for considerable wave action well inside the entrance. The wave environment is therefore a mixed one comprising ocean swell which penetrates through the entrance, at times along the entire length of the harbour, and short-fetch wind waves generated within the harbour and often well developed at the head of the harbour in shallower water.

The pattern of oceanic circulation, or mean flow, on the east coast of the South Island is from the south in the form of the Southland Current (Heath, 1972), and is augmented by the flood tide which advances in a north-easterly direction along the continental shelf (Carter and Herzer, 1979). Pegasus Bay, adjacent to Lyttelton Harbour, is in the lee of Banks Peninsula and tidal flow in this region is therefore weak (Hydrographic Office, 1953). Some evidence exists for an anticlockwise gyre in Pegasus Bay (Carter and Herzer, 1979), a notion which tends to be supported by the tidal wave flooding from an oblique, northerly angle into the entrance to Lyttelton Harbour.

The Canterbury shelf is 40-85 km wide and is a broad, featureless area with little relief (Carter and Herzer, 1979). Thus deep sea southerly swell moves freely up the coast and is refracted around Banks Peninsula, producing a distinct easterly component in Pegasus Bay (Dingwall, 1974). Typical southerly swell has 10-22 second periods and reaches heights of 1-2 m (Carter and Herzer, 1979), although Burgess (1968) observed that refraction around the peninsula is accompanied by a decrease in swell height. Wave periods in excess of 10 seconds are frequent in Lyttelton (Wallingford Hydraulics Research Station, 1979).

Net sediment movement on the Canterbury shelf is northward with the present day flow of sediments mainly into Pegasus Bay (Herzer, 1981). Coarser, sandy sediments being transported north or reworked around Banks Peninsula are deposited mainly in a broad sand ribbon off the eastern end of the peninsula, while a modern mud facies is deposited in quieter regions and has reached its greatest thickness in Pegasus Bay (Herzer, 1977, 1981). Thus marine sediments adjacent to the entrance to Lyttelton Harbour comprise very fine muds.

1.2.1 Previous Studies of Lyttelton Harbour

Little attention has been given to the hydrodynamics and sedimentation in Lyttelton in any detail, although several studies have commented briefly on unusual tidal and sedimentary patterns.

Williams (1915; 1930), in general reports on harbour developments, stated that siltation within and at the entrance to the inner port was most rapid in excavated areas exceeding 6.5 m, and non-existent in areas where depths were less than 2.5 m. He found the cause of siltation to be rough weather wave action agitating bottom sediments, while observed increases in depths towards the head of the harbour were attributed to effects induced by construction of port moles, which allowed larger waves to pass further up the harbour.

Cotton (1949) was the first to observe the "abnormality" of conditions within the harbour compared to most other 'drowned' or embayed coastal inlets. He noted the presence of a range of wave conditions, caused by ocean swell, which travelled the entire length of the harbour with only slight refraction, and attributed these conditions to the bed materials and the nature of bed accumulation. This was atypical in that fine silts did not grade into course sand beaches at the sides, and the bottom had not assumed any degree of shelving. Cotton concluded that these factors were the result of the volcanic and erosional origins to the harbour.

Brodie (1955) conducted the first major examination of sedimentation, based largely on sedimentary and bathymetric comparisons between charts dating from 1849 to 1951. From these data he inferred processes and responses in the harbour. The study pointed out various regions of erosion, deposition, or equilibrium over the period examined, and Brodie concluded that sediment infilling the harbour was derived mainly from the local catchment but no net increase in sediment volume had occurred since 1849. He considered that the quantity removed by dredging was equivalent to that brought down off the catchment. The study also highlighted a well-defined boundary between a mud bottom north of the harbour centre line and a sand bed south of the centre line. Brodie felt this sediment distribution was indicative of a more rapid tidal stream on the southern side, although the flat form of the bed indicated a controlling influence by both waves and tidal currents.

A study by Garner and Ridgway (1955) carried out a series of investigations into tidal current velocities and circulation patterns utilizing dye trails and float tracking. A strong ebb flow was found to be concentrated on the south side of the entrance, with evidence for circulatory currents outside the entrance deflecting water into the harbour. Current speeds were generally less than 0.25 ms^{-1}, with flood velocities increasing from 0.1 ms^{-1} at the entrance to 0.21 ms^{-1} opposite the port. The flood stream was dominantly on the southern side, and was inferred to be carried throughout the water column while evidence of layered flow in the ebb tide was found by float tracking on the northern side. The study was not detailed however, because decay of the dye provided a limited tracking period of only a few hours.

Bushell and Teear's (1975) study provides the most recent survey on sedimentation in a study on dredging and 'regime improvement'. Data were obtained from a sediment survey, dredging records, sounding charts, current metering, wave refraction analysis, and diver observations. From these it was inferred that "...the tidal currents are the primary transporting agents...and the principal determinant of sediment mobility is wave action". In respect of the latter mechanism, it is interesting to note that yearly variations in channel siltation rates were thought to depend largely on the weather. Recorded current velocity data obtained by Bushell and Teear conflict with Brodie's inferred tidal speeds. The data show an imbalance on the northern side, with a greater volume of water passing on the ebb than the flood. This was attributed to longer duration and higher velocities of the ebb tides.

Two studies examined aspects of the physical parameters of Lyttelton in comparison with other New Zealand harbours and inlets in an effort to derive measures for classifications. Heath (1975) examined the stability of 20 tidal inlets by deriving a relationship between tidal compartments and entrance cross-sectional areas. Lyttelton was one of four harbours which did not conform to the relationship, having a cross-sectional area which was comparatively too large for its tidal entrance. Heath (1976a) subsequently ascribed this characteristic to the persistent swell at the harbour entrance, together with a reduced sediment supply.

The harbour was further classified by Heath (1976b) in a broad scale comparison of 32 New Zealand inlets. Circulation patterns were grouped according to ratios of the physical parameters of tidal volume (MLWS), tidal compartment, entrance width, surface area, and inlet length and average width. Heath established a β index (a ratio of tidal compartment, to volume at MLWS) and divided the inlets into two groups; those with $\beta < 4$ in which tidal flow dominated, and those with $\beta > 4$ in which other motions might be of importance. Lyttelton was classified in the latter group, which was further subdivided according to the other physical parameters listed above and Lyttelton was classed as a harbour most likely to contain a vertical, two-dimensional, wind derived motion.

Hydraulic responses in Lyttelton to external forcing are discussed in three papers by Heath (1976c, 1979, 1982), in particular with reference to harbour resonance and oscillations superimposed on the tidal wave. Heath (1976c) analysed the responses of several harbours to the 1960 Chilean tsunami and found a significant oscillatory response in Lyttelton. Harmonic analysis of tidal records determined the dominant amplitude in the response to be in a band with a frequency around 160 minutes, and with significant power also at 96 and 16 minute frequencies. The latter two bands correspond to quarter and half wavelength harbour resonator nodes respectively, but the 160 minute peak is significantly larger than the quarter wavelength resonance. In subsequent analyses Heath (1979, 1982) found a 2-3 hour oscillation in other tidal records for Lyttelton, and concluded that it existed as the result of continental shelf edge-wave effects.

Remaining work accomplished on the hydrology and sedimentation in Lyttelton is in the form of four reports produced by the Wallingford Hydraulics Research Station (1953, 1954, 1955, 1979) for the Lyttelton Harbour Board. These comprised analyses of a scale model of the harbour which was constructed to assess siltation rates, wave conditions, and current patterns for a number of port construction schemes. Utilization of prototype data in these experiments meant they contributed little additional data on the dynamics of the harbour in its natural state.

It is apparent from this review that work accomplished has concentrated on the hydrology and has primarily involved measurements of waves and currents, and some analysis of the tidal wave. A full understanding of circulation within the harbour is yet to be achieved, and the mechanics of sedimentary processes and harbour stability have neither been studied nor measured to date.

1.3 AIMS AND APPROACH

Three general objectives to the study have been outlined in the introduction to this chapter. In order that the thesis should contribute to both the applied field (harbour dredging and management) and the more theoretical field (harbour processes and dynamics), the following specific aims were established:

(a) To determine the sources of sediment supply to the harbour and to assess the relative contributions of these sources to harbour sedimentation.

(b) To establish rates of harbour sedimentation and channel siltation, and determine the immediate source of sediment supplied to the channel.

(c) To determine the nature of circulation patterns within the harbour and the driving forces behind them.

(d) To determine the hydraulic processes inducing sediment erosion, transport, and deposition and establish the mechanics involved in sediment transport around the harbour.

(e) To analyse distribution patterns of sediment erosion, transport and deposition, and determine the effects of internal sedimentation patterns on harbour stability.

(f) To investigate the existence of two separate phases of stability or equilibrium; historical and contemporary.

(g) To examine dredge spoil dispersal patterns and determine the effects of dredging operations on the harbour dynamics and stability.

(h) To determine the effects of a hard rock geometry on circulation and sedimentation patterns and on harbour stability.

(i) To define or classify Lyttelton Harbour in terms of its dynamics and structure, in the context of inlet literature.

The approach to achieving these aims is to conduct investigations into hydraulic and sedimentary processes utilizing both Eulerian (measurement of motion past a point) and Lagrangian techniques (following the paths of individual particles). The use of both forms of measurement enhances the ability to relate general distribution patterns throughout the harbour, of either sediments or water circulation, to processes measured at a variety of discrete points, and *vice versa*. Relationships between hydraulic and sedimentary characteristics of the harbour can then be established.

It is the intention of the study to go beyond the absolute measurements and analysis of physical processes, and to examine interactive responses of processes to the solid boundary geometry of the harbour. Internal dynamics will be correlated with external forces (e.g. meteorological events) and internal phenomena such as dredging, and responses to these variables within the harbour boundaries will be analysed. A model for sedimentation within this type of environment, taking into account the extraneous variables, is developed in the thesis, and examined using prototype data. Finally, in an effort to classify and define the harbour, a number of 'rules' pertaining to the dynamics and stability of the inlet are proposed as a theoretical starting point to understanding similar forms of inlets.

1.4 THESIS FORMAT

The remainder of the thesis is divided into seven chapters. The following chapter is devoted to a brief review and discussion of estuarine and inlet classifications, concepts and literature.

Chapter three is the first of three 'data' chapters and examines historical and contemporary sedimentation patterns, sediment texture and textural properties, and sediment origins. Possible inferences on transport patterns which can be drawn from the sediments are also investigated.

Salinity structure is considered in chapter four and the notion that Lyttelton might fit an estuarine classification is explored. Tidal phenomena in the form of currents and the tidal wave are also examined, and the driving forces behind the tides and circulation patterns are analysed. Tidal circulation is described.

Chapter five examines the wave environment in the harbour, and then addresses the combined hydraulic and sedimentary data from all three chapters, analysing and describing the causes and processes involved in harbour sedimentation.

Sedimentation processes are taken a step further in chapter six where the concept of harbour stability is explored. A model is proposed for the transport and deposition of fine grained sediments utilizing the concept of "sediment flux gradients", and the effects of large quantities of sediment being transported and redistributed within the harbour on harbour stability are assessed.

In chapter seven, management and scientific approaches to coastal inlets are discussed with respect to Lyttelton, and inlet classification schemes are assessed in the context of this study. Lyttelton Harbour is defined, and a general set of principles relating to this type of inlet are proposed as a working hypothesis applicable to other similar environments. It is intended that these principles should provide a basic starting point towards any management or scientific approach to the study of such an inlet.

Conclusions to the study are presented in chapter eight, along with an appraisal of the study and suggestions for future research.

TWO

ESTUARINE PROCESSES

In chapter one it was noted that Lyttelton Harbour contains a number of characteristics which make it "different" from other inlets discussed in the literature in terms of dynamics and stability. Therefore, the main methodological problem associated with this study lies in the use of established principles to examine a new type of system which, apparently, cannot be readily explained using established inlet concepts. The purpose of this chapter is to review the established concepts relating to circulation and sedimentation in inlets to provide an understanding of those principles which are relevant to Lyttelton, and to determine why other principles and concepts have no relevance to the Lyttelton system. The bulk of the discussion centres on estuaries, largely because it is in this area that most research has been undertaken.

2.1 DEFINITIONS

It is appropriate to begin by examining inlet definitions, and classifications (in the following section) because the problem of explaining how Lyttelton Harbour operates, begins with determining what it is to be defined as and how it is to be regarded as a coastal system. To be able to differentiate Lyttelton from other types of inlets in the first instance, a review of definitions and classifications is essential. The exercise is not a trivial one for three reasons:

(1) It has already been shown that Lyttelton is distinctive. This will be demonstrated further in later chapters, and the features described thus far can be compared with the concepts reviewed below.

(2) It is necessary at the outset of the study to determine which established concepts and principles are applicable to this study and which may be useful in analysing Lyttelton Harbour. Thus the principles need to be outlined.

(3) Once the processes controlling the harbour dynamics have been determined from the study results, the problem arises of how to define and classify Lyttelton Harbour and other inlets of its type. A review of existing classification schemes will help to clarify those aspects of Lyttelton which are different, and those upon which a new classification may be based.

Bruun and Gerritsen (1960) define a tidal inlet as;

> ...the waterway connection between the sea and a bay, a lagoon, or a river entrance through which tidal and other currents flow.

As Bruun (1978) notes, practically all coastal inlets may be classified as "tidal". Therefore the classification of various types of inlets is of necessity dependent on parameters other than those of tidal related phenomena. For example, Bruun (1978) differentiates tidal inlets on littoral drift shorelines from those on non-littoral shores because of varying sediment supplies and the corresponding inlet responses to those supplies. Undoubtedly, the most well known and frequently studied type of tidal inlet is the estuary. However, this category has become extremely broad. Where the term was traditionally applied to the lower reaches of a river into which sea water intrudes and mixes with fresh water draining seaward from the land, it has now been extended to include bays, inlets, gulfs, and sounds into which several rivers empty and in which the mixing of fresh and salt water occurs (Cameron and Pritchard, 1963). The definition of an estuary may also vary depending on a researcher's viewpoint, as Caspers (1967) points out when assessing biological considerations.

Schubel and Pritchard (1971) examined the estuarine definitions and discarded them on the basis that they were all either too inclusive or too exclusive of the inlets they could be applied to. The most widely accepted definition, by its general usage, is that given by Cameron and Pritchard (1963):

> An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and within which the sea water is measurably diluted with fresh water deriving from land drainage.

Pritchard (1967b) argues for the acceptance of the above definition over others, as it meets the requirements that;

> From a physical standpoint, the definition of an estuary should recognise certain basic similarities in the distribution of salinity and density, as well as the circulation pattern and the mixing processes; it should point out also the importance of the boundaries which control the distribution of properties and the movement and mixing of waters.

However, the definition does not allow for a distinction between immobile and mobile boundaries which in the longer term will influence circulation patterns and inlet stability to markedly differing degrees. Many inlets contain only a single mobile boundary at the bed, but coastal literature provides no definition to distinguish the processes in these types of inlets from those in more structurally mobile inlets.

Fischer (1976) found the definition inadequate, "...as it excludes such estuaries as San Diego Bay where the fresh water flow is less than the evaporation, but which can be treated like other estuaries with respect to mixing problems". The comment introduces an interesting paradox in the context of this study, because estuarine mixing processes are dependent on the tides and river flow and are driven by density differences between fresh and salt waters (Dyer, 1973). If in fact the saline water in San Diego Bay is not 'measurably diluted with fresh water', the implication is that mixing processes are tidally driven only; which is thought to be the situation in Lyttelton Harbour where mixing might be defined in estuarine terms. However, it is argued in chapter four that Lyttelton is not an estuary. Clearly the definition provided by Cameron and Pritchard (1963) fails to differentiate between estuarine and non-estuarine inlets, in terms of the processes operating, at one end of the estuary spectrum. This is the 'well mixed' end of the estuary classification scheme from Pritchard (1952, 1967a), which is discussed below with other proposed schemes and with the parameters which determine the classifications.

2.2 INLET CLASSIFICATION SCHEMES AND PARAMETERS

The purpose of scientific classification is to group, and explain the grouping, of like phenomena in terms of the simplest set of basic principles which demonstrate the important similarities between the phenomena and enable them to be grouped as one class or type. Thus with coastal inlets, classification schemes have been developed based on structural or hydraulic parameters to group inlets which are alike in their formation, or operation, or both.

Several classifications for estuaries have been proposed based on both structure, or topography, and salinity structure. Pritchard (1952) presented one based on topography, dividing estuaries into the three groups; coastal plain estuaries, fjords, and bar-built estuaries.

Coastal plain estuaries are formed by drowning of former river valleys, and are usually an elongated indenture in the coastline with a river flowing into the upper end. Typically they are rather shallow and often have a dendritic shoreline. Fjords are elongated indentures in the coast containing a deep basin with a shallow sill at the mouth, while the third group result from the development of an offshore bar on a shoreline of low relief and shallow water. This last group usually possess a very narrow channel, which links the estuary with the open sea.

To this classification scheme, Dyer (1973) has attached an additional category entitled "The Rest". He states (p.6):

> In this section one can include all estuaries that do not conveniently fit elsewhere. Included are tectonically produced estuaries: estuaries formed by faulting, landslides and volcanic eruptions.

Lyttelton Harbour could conveniently be fitted into this category, but clearly this would be unsatisfactory. The category characterises inlets such as Lyttelton in terms of what they are not, rather than in terms of inherent characteristics which control circulation, sedimentation, and stability. Given that the set of principles forming the basis for a classification should provide the starting point to defining what an inlet is, and how it works, such a category is totally negative and reflects the paucity of knowledge germane to inlets like Lyttelton Harbour.

Bowden (1967), Hansen and Rattray (1966), Pritchard (1955, 1967a) and Schubel (1971) have all given classification schemes for estuaries based on salinity structures and mixing. In hydrodynamic terms, all distinguish three major categories; sharply stratified estuaries, such as fjords and salt-wedge estuaries; partially stratified or partially mixed estuaries, in which there is a significant vertical density gradient and vertical mixing is inhibited; and well mixed estuaries.

Pritchard (1955, 1967a) described an estuarine sequence with four types of estuaries in it. A type A estuary (highly stratified) is characterised by a river flow dominated circulation pattern. A salt water wedge can be identified in this type, extending beneath the seaward flowing upper layer. Salt water is advected into the upper layer from the wedge, but there is little or no mixing of fresh water down into the wedge. Tidal mixing is relatively unimportant in this type of estuary. However, tidal mixing plays an important role in the circulation of type B estuaries (moderately stratified). Mixing occurs between the upper, seaward flowing layer and the higher salinity water flowing up the estuary along the bottom. Volumes of flow involved in this net circulation pattern are often many times greater than the volume of fresh water inflow.

Type C estuaries have intense mixing which breaks down the stratification, forming a vertically homogeneous water column. In these estuaries Pritchard states that lateral flow patterns develop, with lower salinity outflow occurring on one side and a compensating higher salinity flow on the other. Lateral advection and lateral eddy mixing of salt takes place. The type D estuary is an extension of the vertically homogeneous estuary, in which lateral mixing is sufficient to destroy the lateral salinity gradient and the estuary may be regarded as both vertically and laterally homogeneous.

Pritchard (1955) concluded that, all other things being constant, it is possible to shift through the sequence from type A to type C or D as functions of; decreasing river flow; increasing tidal velocities; increasing width; or decreasing depth.

Bowden (1967) has adopted the same classification scheme as Pritchard, but expands on type B estuaries. He divides this class into two parts; those estuaries having two-layered flow with entrainment, and those having two-layered flow with vertical mixing. The difference exists where in the former case salt water moves into the upper layer but fresh water does not mix downwards. A thin layer of mixing, the halocline, may exist, and salt water will be entrained upwards at the base of the halocline. Fjords are of this type. In the latter case, usually in shallow estuaries where tidal mixing is more pronounced, mixing occurs throughout the water column transferring fresh water downwards and saline water upwards. The key difference between the two is in the level of turbulence throughout the depth of the estuary.

Both Bowden (1967) and Schubel (1971) examine in some detail the mixing concepts relating to estuaries, and to Pritchard's estuarine sequence. Schubel examines the same sequence in terms of a "mixing index" defined as the ratio of the volume of fresh water entering during a half tidal period to the volume of water entering during a flood tide. He observes that an estuary in which the mixing index is greater than or equal to one will probably be highly stratified, while indices less than one, and substantially less than one will belong to partially mixed and vertically homogeneous or well mixed estuaries respectively. Schubel notes that the upper limit for a type C estuary is probably about .05. Other authors have used variations of the mixing index; for example Simmons (1955) defines a "mixing ratio" as the ratio of the volume of upland water entering an estuary for conditions of mean upland discharge over the interval of a mean tidal cycle of about 12.42 hours to the mean tidal prism of the estuary.

An alternative classification scheme is provided by Hansen and Rattray (1966) based on theoretical derivations. Essentially the scheme is based around a parameter, V, which is the ratio of the tidal diffusion salt flux to the total up-estuary longitudinal dispersion salt flux. When V = 1, the up-estuary longitudinal dispersion flux is due entirely to tidal diffusion, and as V tends towards zero the dispersion flux is due almost entirely to the net circulation effects. V is calculated from tidal averaged salinity, net circulation velocity, and averaged river runoff data, and may be used to determine the extent of mixing in an estuary.

Few classifications exist for, "non-estuarine", inlets. Caldwell (1955) provides a classification specifically for inlets which do not have sufficient fresh water flow to distort the tidal action. He derived three classes based on empirical relationships relating to the strength of flood currents in the inlet entrance and the ratio of the tide range within the inlet to the external tide range. The classification is designed to estimate the 'adequacy' of the entrance, and is a measure of the internal size of the inlet related to the size of the entrance.

Heath (1976b) classified New Zealand inlets, initially on the basis of whether tidal flow dominated any other flow by utilizing the ratio of the total water volume to the spring tidal compartment. Those inlets with predominantly tidal flow were then subdivided into categories on the basis of inlet dimensions, and from this Heath predicted the main driving forces in terms of tidal and wind derived motion or boundary forcing.

Undoubtedly the most widely used classification scheme is that of Pritchard (1955) for estuaries. The scheme has limitations however, in terms of its usefulness in describing estuaries. As it is based solely on salinity structure, it provides only a very general idea of the type of circulation which can be expected in a given estuary. It supplies no information on the magnitude of flows, the extent to which one type of flow dominates another, or what processes of sedimentation are operating. This comment can be made equally for other classifications based on mixing or inlet structure. While the basic principles are useful to apply in a study, they do not provide ready answers to questions relating to the internal distribution of sediments, internal inlet stability, or the mechanics of changes in sedimentation or stability processes when inlet geometry or boundary changes are made. The limitations of these classifications are particularly highlighted at the well mixed end of the sequences, where distinctions between a well mixed estuary for example, and an inlet such as Lyttelton Harbour are not at all clear.

2.2.1 Circulation and Mixing Processes

An abundance of literature has been presented in the last few decades on inlet circulation and mixing, again related primarily to estuaries. As with classification schemes, the broader concepts of circulation and mixing have been largely ignored in non-estuarine inlets, where hydraulic factors are frequently described only in terms of local tidal effects. As a consequence, general principles relating to the controls and effects of circulation in non-estuarine inlets, particularly with respect to sedimentation, are imprecise and infrequently applied. It is therefore appropriate to review existing circulation and mixing concepts since one of the aims stated in chapter one is to derive basic principles which will enable classification of the type of inlet being studied.

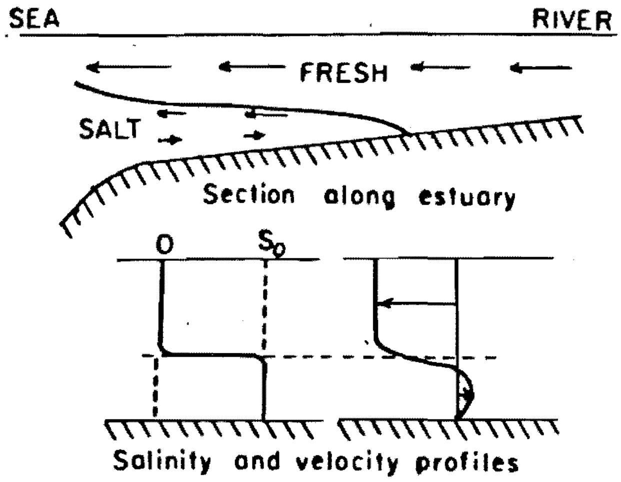
Bowden (1960, 1967, 1977), Dyer (1977), Fischer (1976), Gardner and Smith (1978), Garvine (1977), Hansen (1967), Hansen and Rattray (1965), Ketchum (1952), Officer (1977), Pritchard (1955, 1967a), and Rattray (1977) have all examined aspects of circulation and mixing in various types of estuarine environments. From these, the traditionally accepted estuarine circulation patterns are outlined below.

Figure 2.1 shows circulation patterns and salinity and velocity profiles for typical stratified, partially mixed, and well mixed estuaries. In stratified or salt wedge estuaries, the salt water extends as a wedge into the river, beneath the less dense fresh water. The water interface between the two layers slopes slightly downwards in the upstream direction, and the steep density gradient at the interface reduces turbulence and mixing to a very low level (Bowden, 1967). Because of the velocity shear across the interface, a thin layer at the top of the salt wedge will be swept seawards. When the shear is sufficiently intense waves form and break on the interface and saline water is mixed into the surface fresh water (Dyer, 1973). This process is called entrainment and is a one-way process. However, in order to preserve continuity a slight compensating landward flow is necessary in the salt wedge (see Figure 2.1A) to replace the salt water passing into the upper layer.

Where tidal currents are of sufficient amplitude to induce mixing throughout the vertical depth of the estuary, a partially mixed condition exists and there is a two-way exchange of fresh and salt water at the interface. Thus mixing is a function of tidal oscillation within the estuary, and the degree of mixing is a function of the ratio of tidal currents to river flow (Bowden, 1967), or of tidal prism to estuary volume (Dyer, 1973). Because of the efficient exchange of fresh and salt water, the salinity of both upper and lower layers increases towards the sea, although at any given point the bottom layer is always higher in salt content than the upper layer (Pritchard, 1967a). Undiluted fresh water only occurs very near the head of the estuary, unlike the salt

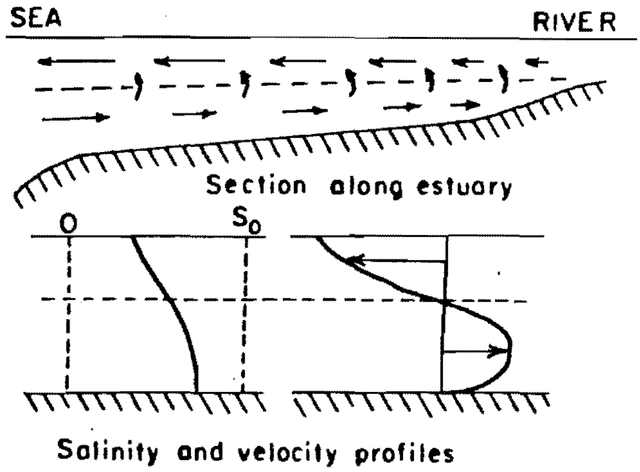
(A)

Salt wedge estuary



(B)

Partially mixed estuary



(C)

Well mixed estuary

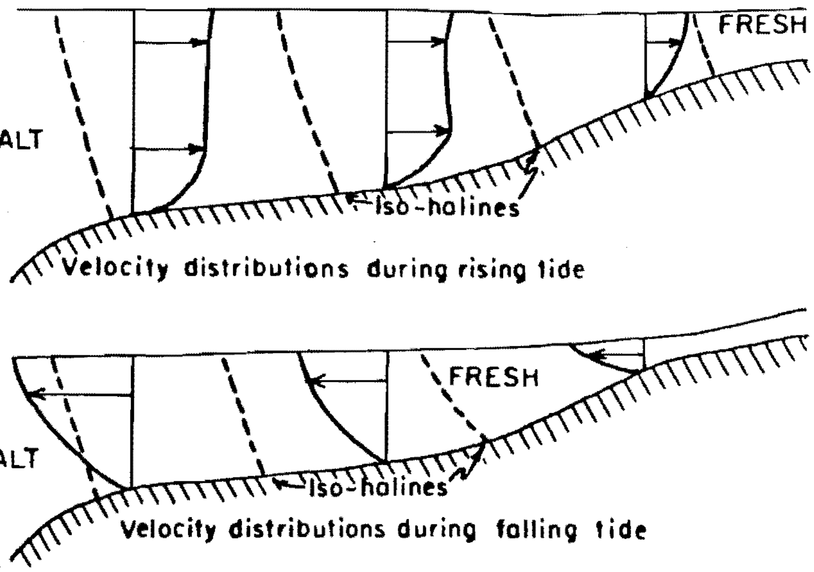


Figure 2.1 Typical salinity and velocity profiles in estuaries.
A and B: After Bowden (1967)
C: After McDowell and O'Connor (1977).

wedge estuaries where the river flows over the salt water (Dyer, 1973). A partially mixed estuary therefore has no marked interface with the salinity profile showing a continuous increase from the surface to the bottom. The maximum salinity gradient occurs near the level of no net motion between the seaward flowing upper layer and the landward flowing bottom layer (Bowden, 1967).

Two-way circulation in stratified and partially mixed estuaries is thus the result of density differences between the two water bodies, tidal mixing, and salt balance. Circulation is more pronounced in partially mixed estuaries because the mixing contributes a greater volume of salt water to the upper, seaward flowing layer than in a salt wedge estuary. The rate of flow in the upper layer of the partially mixed estuary is therefore much greater in volume, necessitating a correspondingly larger landward flow in the lower layer (Pritchard, 1967a). This replaces the salt water lost and maintains the continuities of volume of water and mass of salt. Hansen (1967) examines in detail the salt balance and circulation in partially mixed estuaries.

When tidal mixing is sufficiently vigorous, for example in macrotidal or very shallow estuaries, the vertical salinity stratification breaks down and the estuary approaches true vertical homogeneity, or a well mixed condition. However, because the well mixed condition results in no density gradients or layers of water, no two-way circulation patterns exist in these estuaries, which are shown in Figure 2.1C. Pritchard (1967a) states:

> The processes which ultimately control salt distribution in such an estuary are imperfectly understood. In the absence of a vertical salinity gradient, we tend to think not of vertical mixing processes, but of lateral and

> longitudinal transfer of salt (by advection or non-advective processes) as the controlling factors. However, vertical mixing must be invoked to account for the vertical homogeneity. The difficulty may lie in an inadequate mathematical or conceptual representation of the processes of non-advective flux.

Later Pritchard observes that;

> It is evident that the salinity distribution is closely linked to the eddy frictional forces set up by the vigorous tidal mixing.

In essence it would appear that authors have had some difficulty in arguing the existence of well mixed estuaries as "estuaries" rather than as "tidal inlets" per se. The main criterion for the classification appears to be a longitudinal salinity gradient, but in terms of processes there seems to be little evidence to support a "well mixed estuary" classification. While a number of authors have presented data from studies of "well mixed estuaries", or estuaries which are in part well mixed either temporally or spatially (e.g. Anwar, 1983; Bowden, 1960, 1967; Castaing and Allen, 1981; Conomos and Peterson, 1976; Dronkers, 1978; Duke, 1961; Haas, 1977; Hughes, 1958; Kent, 1960; Odd and Baxter, 1980), some authors have suggested that well mixed estuaries may technically not even exist (e.g. Dyer, 1973; Pritchard, 1967a).

Of more importance to the present study is the identification of the main processes operating in this type of inlet. Proposed factors maintaining the longitudinal salt balance in well mixed estuaries are ebb and flood tidal flow asymmetry (Dyer, 1973; Pritchard, 1967a), or the trapping of salt in bays and creeks and its subsequent 'bleeding' back up the estuary (Dyer, 1979). Dyer (1977), in a study on lateral circulation in estuaries, found significant phase and cross-sectional area relationships between tidal variations of salinity and velocity. Dronkers (1978), found that dispersion processes occurred mainly as a consequence of the tidal motion and the inlet geometry, and Fischer et al. (1979) state that the primary flow in estuaries is driven by the slope of the tidal wave. Given the apparent similarities between well mixed estuaries and Lyttelton, these processes may be as relevant to sedimentation in non-estuarine inlets as to salt dispersion in estuaries. They will therefore be applied to aspects of this study, and be examined in terms of the classification of Lyttelton Harbour and well mixed estuaries in chapters six and seven.

There seems little doubt therefore, that in process terms a well mixed estuary is largely tidally controlled, which raises the issue of how such inlets differ from Lyttelton Harbour, which is a non-estuarine tidal inlet (Section 4.1). Furthermore, with respect to factors such as sedimentation and inlet stability, the placement of such inlets in an estuarine sequence may be misleading from the approach and perspective point of view for any study. The tidal mechanics operating in an inlet such as Lyttelton may in fact be more pertinent to the dynamics of well mixed estuaries than circulation and mixing concepts which are applicable to stratified and partially mixed estuaries.

2.2.2 Sedimentation Processes

A feature of estuarine sedimentation patterns is the control exerted on sediment distribution by the landward limit of the fresh water salt water interface. In salt wedge estuaries bedload sediment from river discharge is deposited at the tip of the salt wedge, although because the position of the salt wedge is dependent on the river discharge, sediments become spread over a long distance with time. Fine sediments are generally carried out to sea (Dyer, 1979). In partially mixed estuaries, the "turbidity maximum" controls sediment distribution. This phenomenon is traditionally associated with estuarine sedimentation, and represents a zone within which the suspended sediment concentrations are higher than those in the river or the sea (Inglis and Allen, 1957). It is located near the head of the salt intrusion and alters its position with changes in river discharge; its existence usually being due to hydrodynamic conditions (Postma and Kalle, 1955; in Postma, 1967). Sediment is introduced into the upper estuary by the river and the vigorous mixing exchanges the sediment into the upper layer where the seaward flow causes downstream transport. In the middle estuary the sediment settles into the lower layer in areas of less vigorous mixing and joins sediment entering from the sea in the bottom, landward residual flow (Dyer, 1979). It then moves back towards the head of the estuary. This action forms a very effective sorting mechanism and the size range of particles in the turbidity maximum is narrow (Schubel, 1969). There are considerable areas of mud flats in the region of the turbidity maximum although deposition of sediment will not necessarily occur. Vertical mixing may eventually bring a particle back to the surface layer and either the process will be repeated or the particle will escape to sea (Postma, 1967).

Few studies have analysed estuarine sedimentation processes. Guilcher (1967) examined the origin of sediments in European estuaries, while texts by Dyer (1979) and

McDowell and O'Connor (1977) review sedimentation processes and the associated literature. Emphasis on processes in these reviews is placed on sediment properties such as erosion resistance and floccule settling characteristics. However, the actual processes of sediment distribution have been largely ignored. Many case studies have leaned heavily on the existence of a turbidity maximum to explain sedimentation patterns without examining the processes operating.

Nowhere is the lack of knowledge on estuarine sedimentation processes more evident than in well mixed estuaries. Dyer (1979) considers the turbidity maximum to be a feature of well mixed estuaries, and some studies (e.g. Inglis and Allen, 1957; examining the Thames estuary) reflect this approach to sedimentation in well mixed estuaries. However, considering the degree of mixing in this type of inlet the limit of salt intrusion, and therefore the possible region for a turbidity maximum, is likely to be hard to define. In a study on sediment transport and sedimentation in estuarine environments, Postma (1967) considers that the "mixed" parts of an estuary closely resemble tidal areas in terms of sedimentation. More recently studies by Allen et al. (1980), and Castaing and Allen (1981) in the Gironde estuary, a macrotidal estuary, and by Gelfenbaum (1983) in the Columbia River, a mesotidal estuary, indicate that tidal cycles play an important role in estuarine sedimentation. The Columbia River is a partially mixed estuary where Gelfenbaum established a relationship between sedimentation patterns and the strength of the turbidity maximum which corresponded to the fortnightly spring neap tidal cycles. More importantly, in the Gironde estuary Allen et al. (1980)

and Castaing and Allen (1981) report that during spring tides or low river flow the estuary changes from partially mixed to well mixed. At these times they consider tidal currents and tidal phenomena such as ebb-flood asymmetry, spring-neap cycles or lateral flow asymmetry, to be at least as important to sedimentation as density current phenomena. Allen et al. (1980) state that in certain cases tidal currents can induce features of the classical "estuarine" sedimentation patterns.

Several sedimentation models have been proposed for tidal inlets, and have generally been applied to well mixed estuaries. In all cases they reflect a response to tidal phenomena. They are reviewed briefly here, and discussed in detail in chapter six where they are applied to the problems associated with sedimentation and stability in Lyttelton, and assessed in terms of their adequacy in accounting for those characteristics of Lyttelton which differentiate it from other inlets.

Distortion of the tidal wave as it propagates up a relatively shallow estuary induces a marked ebb-flood asymmetry in the upper reaches of the estuary (McDowell and O'Connor, 1977). This increases peak flood velocities relative to the ebb, and can contribute to the landward transport of bottom sediment (Groen, 1967). In the absence of density circulation this process can induce a typical "estuarine" sediment trap (Castaing and Allen, 1981). The concept of a net sediment transport in one direction due to tidal asymmetry was examined by Van Straaten and Kuenen (1958) and Postma (1961), who proposed a "scour lag" and a "settling lag" model for net sediment transport in the Wadden Sea. They suggested that suspended sediment carried by a flood tide would continue to be transported landward while settling, after the flood velocities had become too slow to carry the suspended load. Subsequently, ebb currents flowing off the tidal flats are initially insufficient to entrain the deposited particles again as a higher velocity is required to erode them than to transport them. Consequently, as a longer time is required to attain velocities of sufficient strength to erode the deposited sediment, there is less duration on the ebb tide for transporting particles than there is on the flood tide. Thus particles move a lesser distance seaward on the ebb tide than they do landward on the flood. Groen (1967) and Postma (1967) examine this process in some detail. Postma (1967) notes that "in coastal seas a residual component is often present which causes the amount of water carried over the flood to exceed that of the ebb". In the Wadden Sea region, Postma (1981) examined the effects on sedimentation of both turbidity maxima and tidal phenomena and determined that the two combined to trap sediment in the mouths of rivers and on tidal flats. Consequently low concentrations of suspended matter exist within tidal inlets and high concentrations prevail near the coast and in shallow water.

The above model requires a sufficient slack water period for sediment to settle. McCave (1970; 1971) assessed the model and found that it failed to account for very high siltation rates in certain areas. He therefore proposed a model for fine grained sediment deposition during wave activity and current flows of up to 0.77 ms^{-1} at the surface (discussed in detail in Section 6.2).

Data utilized to investigate the above models by McCave, Postma and Van Straaten were derived from tidally controlled, predominantly coastal regions with tidal flats. However, the models have not been applied to coastal inlets such as Lyttelton Harbour. Boon and Byrne (1981) examined net, ebb/flood tide transport in inlet channels in relation to inlet hypsometry (or an area-height representation of the basin storage-volume). Gallivan and Davis (1981) examined sediment transport in a microtidal estuary and found a net landward transport related to tidal flow asymmetry. However, such studies have examined inlets which contain fully mobile boundaries, unlike Lyttelton. Whether the sedimentation models are applicable to Lyttelton Harbour and the stability of the harbour has not been demonstrated in the literature. Studies by Allen et al. (1980) and Castaing and Allen (1981) have demonstrated the applicability of tidal sedimentation models to the Gironde estuary when it is in a well mixed condition. Overall sedimentation patterns in this estuary are complicated by the turbidity maximum under partially mixed conditions so that the long term response of the inlet to tidal phenomena alone cannot be analysed.

A large number of case studies also exist which relate to sedimentation in non-estuarine tidal inlets. Predominantly they relate to inlets which are located on littoral drift shorelines and have fully mobile boundaries. This emphasis is reflected in texts on this type of inlet by Bruun (1966; 1978) and by Bruun and Gerritsen (1960). Frequently tidal asymmetry is found to induce a net sediment transport, as might be expected (e.g. Davies-Colley and Healy (1978b) found that sediment dynamics were largely a function of tidal current asymmetry in the entrance to Tauranga Harbour). However, it must be reiterated that there is a notable absence of the application of sedimentation models to inlets such as Lyttelton with a single mobile boundary, or for that matter to well mixed estuaries which are apparently controlled more by tidal than by estuarine processes.

Therefore, in the remainder of the thesis the hydrography and sedimentation of Lyttelton Harbour will be examined, and those aspects which are atypical of the inlet literature will be outlined. Where it is appropriate to do so, the circulation and sedimentation models and concepts reviewed in this chapter will be applied to the dynamics of Lyttelton Harbour. However, more importantly, where these models and concepts fail to explain specific problems and observations in the harbour, areas of differentiation will have been identified. It is these areas which will require explanation to enable Lyttelton to be classified as a distinct form of coastal inlet. Thus, classification and approaches to classification will be readdressed in the latter stages of the thesis once the dynamics of the harbour have been outlined.

THREE

SEDIMENTATION REGIME IN LYTTELTON HARBOUR: HISTORICAL CHANGES AND CONTEMPORARY PATTERNS

This chapter examines sedimentation patterns within the harbour utilizing data from sediment texture, grain size and sorting parameters, from direct measurements of suspended sediment transport and distribution, and from catchment erosion rates. It has been pointed out in chapters one and two that the emphasis of inlet research has been on hydrodynamics. However, the description of the distribution of sediments in inlets is demonstrably important for two reasons:

(1) Sediments are an important feature affecting both processes and morphology.

(2) They provide important information as to the processes operating within the inlet.

Thus, interrelationships exist between the hydraulics and sediments in any coastal environment and many process interpretations may be drawn from a description of sediment distribution patterns. Commonly in inlet studies, sediment distribution descriptions are either ignored, or are very general so that they fail to provide detailed information on sediment parameters. It will be seen in section 3.2.2 that the detailed description of sediments, and the plotting of mean grain size contours, also identify Lyttelton Harbour as being distinctive from other inlets, along with other features already discussed in chapter one.

In a discussion of estuarine environments Ippen (1966; p.51) notes that sediment transport is "...a complex series of erosion and deposition, of dispersion and consolidation, variable with the change of tides and of freshwater flow". This can of course be said of any coastal inlet to varying degrees in the short term, but in the long term spatial differentiation patterns of sediments will distinguish differences between one inlet and another, subtle or otherwise. The following sections examine the spatial differentiation patterns in Lyttelton with respect to the harbour morphology and dredging operations. From these data inferences are drawn on sediment sources and transport directions, zones of erosion and deposition are identified, and the historical stability of the harbour is determined from bathymetric data. Throughout the chapter, assessment is made on the adequacy of existing inlet concepts to explain the sediment patterns described.

3.1 HISTORICAL BATHYMETRY: DEPOSITION AND EROSION

Comparisons in bathymetry were made between charts dating back to 1849, allowing analysis of erosional and depositional phases within the harbour both temporally and spatially. From this analysis the historical stability of the harbour was determined. Numerous sounding charts exist, largely collected by the Lyttelton Harbour Board for dredging survey records, but these either have datum inconsistencies or only partially cover the harbour rendering them unsatisfactory for the analysis. Therefore, only four charts were compared for the period 1849 to 1976; Admiralty chart 1999 by HMS "Acheron" (1849); a 1903 chart by C.J.R. Williams, engineer to the Lyttelton Harbour Board; N.Z. Hydrographic chart NZ54 by

HMNZS "Lachlan" (1951); and NZ Hydrographic chart NZ6321 (1976).

Two potential problems arose in the analysis. Firstly, Brodie (1955) notes that the 1849 datum, not stated on the chart, is marginally different to those of later charts. Secondly, the sounding technique altered from lead-lining in 1849 and 1903 to echo sounding in 1951 and 1976. Discrepancies between recordings by the two methods may be a source of error as a lead-line will sink through "fluid" surface muds recorded by an echo sounder. However, section 3.3.2 demonstrates that there are few areas of fluid mud within the harbour. They occur primarily in and around the channel and near the harbour entrance. Discrepancies in measurements would be in the order of 0.05 m if they occurred in fluid mud areas. Variations in datums were accounted for, and in both cases it is felt that errors involved were substantially less than depth differences derived from survey comparisons and the differences were therefore disregarded.

Weggel's (1983) technique was used to analyse changes in sedimentation patterns over time. The analysis involves contouring each chart at arbitrary intervals, calculating the area between contours, and plotting this value against the larger of the two contour values. The areas were calculated by tracing the contours onto graph paper, determining the area of one grid square from the scale of the chart, and multiplying this figure by the number of grid squares between the contours. Thus for each survey a plot is obtained of area less than a given depth against the given depth. Figure 3.1 illustrates these plots. Where the area increases between two surveys scour has occurred, while a reduction in area

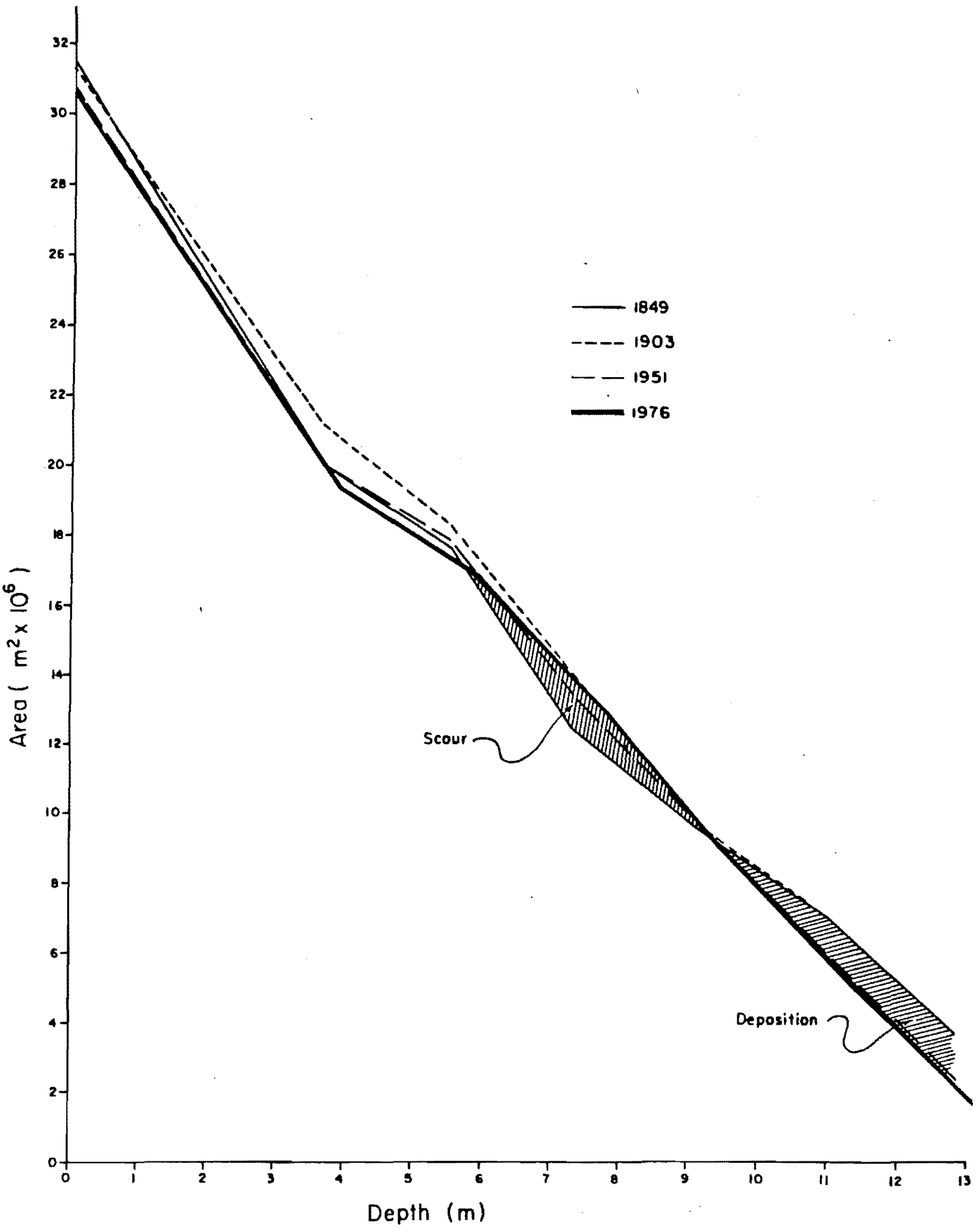


Figure 3.1 Graph of changes in area less than a given depth vs depth through time. Datum is Mean Low Water Neap.

indicates deposition. Plots between any two surveys may be combined and redrawn as one curve depicting erosion or deposition throughout the harbour as a function of depth. From these curves a time series can be generated. Figure 3.2 is a time series depicting an effective illustration of harbour depositional and erosional patterns in both short and long terms. As far as possible the plots shown are an attempt to represent natural harbour processes, and as such the channel was ignored in contour and area calculations, as were the bays on both sides of the harbour east of the breakwater where considerable quantities of dredge spoil have been dumped over the years.

It is apparent from Figure 3.2 that in the long term, 1849-1976, the harbour has functioned in three sections, deposition occurring at both the head and entrance, and scour occurring in the centre. Deviation from this pattern is most noticeable between 1849 and 1903 when considerable scour effects occurred within the middle and upper reaches of the harbour. The cause of this scour is discussed in chapter six; there being influences on hydrodynamics over that time resulting from port breakwater constructions and initial channel dredging programmes. As can be seen from Figure 3.2, response to change was rapid, with a complete reversal to depositional processes after 1903 in the head of the harbour presumably as a level of equilibrium with the altered hydraulic environment was established. Johnston (1969) notes the sale and development of land around Lyttelton Harbour in the late 1800's and early 1900's, and this may have increased catchment erosion and harbour sedimentation levels.

An important point to be made clear from the graphs

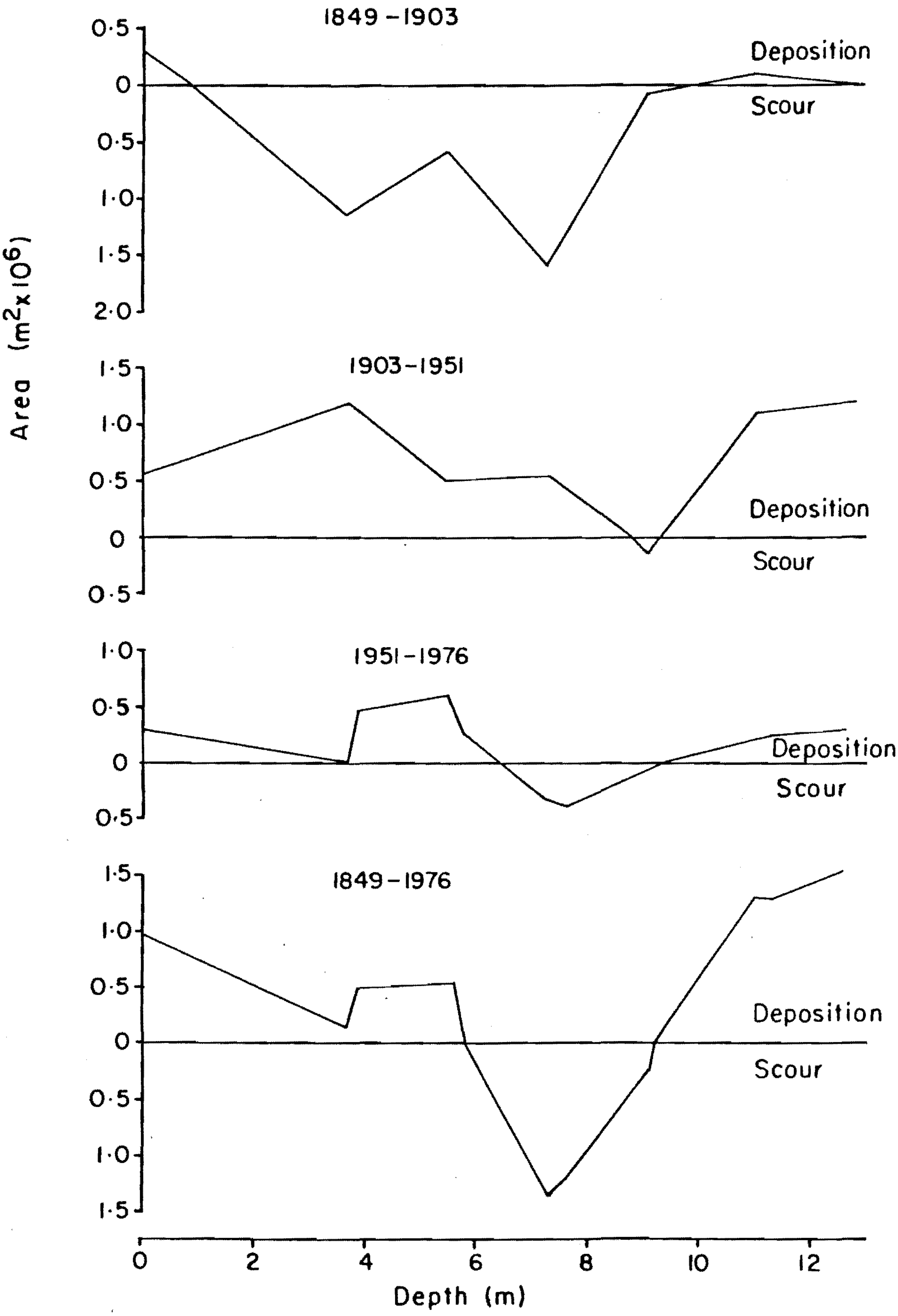


Figure 3.2 Graphs of harbour deposition and scour through time plotted as area less than a given depth vs depth. Datum is MLWN.

is that the actual quantity of 'natural' sediment movement within the harbour, associated with scour and deposition, is very small in relation to channel siltation. Table 3.1 supplies volumes for the graphs in Figure 3.2. It is clear from these figures that the net depositional volume accumulated since 1951 is substantially below any value which might be commensurate with a maintenance dredging schedule of 700,000 to 1,000,000 tonnes annually. (In the conversion of all volumetric data to tonnes, the bulk density figure of 1.68 $gm.cm^{-3}$ was used. It was derived by Williams (1930; p.6) as a specific gravity for the harbour sediments, and is used by the Lyttelton Harbour Board for dredging records.)

Figure 3.3 shows a further breakdown of data into rates of sediment accumulation through time for various sections of the harbour. This shows the harbour behaving consistently in all sections, with the exception of a lack of scour in deeper regions between 1841 and 1903 and scour in the 7.3 - 9.1 m depths since 1965, but at markedly differing rates. Prior to 1951, maximum rates of deposition occurred at both ends of the harbour in the deepest and shallowest regions, while sediment accumulated in the centre at a somewhat reduced rate. Since 1951 there has been a notable decline in sedimentation rates throughout the harbour, particularly at the harbour head and entrance. Again it is apparent that sedimentation, and therefore sedimentary process, is a function of different variables and mechanisms at the head and the entrance of the harbour than in the centre. Causes of variations in sedimentation rates will be discussed in following chapters.

Two inconsistencies in the construction of these graphs should be noted. Firstly, it was assumed that sedimentation

Table 3.1 Volumes of sediment movement in Lyttelton Harbour through time. (Sediment bulk density = 1.68 $gm.cm^{-3}$.)

PERIOD	YEARS	DEPOSITION (Tonnes)	SCOUR (Tonnes)	NET CHANGE	AVERAGE RATES Tonnes. Yr^{-1}	AVERAGE RATES Tonnes. $Km^{-2}Yr^{-1}$
1849-1903	54	335,664	11,606,784	11,271,120 Scour	208,724	6,523
1903-1951	48	16,919,952	68,040	16,851,912 Deposition	351,082	10,971
1951-1976	26	2,828,184	918,960	1,909,224 Deposition	73,432	2,295
1849-1976	128	11,282,880	5,001,360	6,281,520 Deposition	49,074	1,534

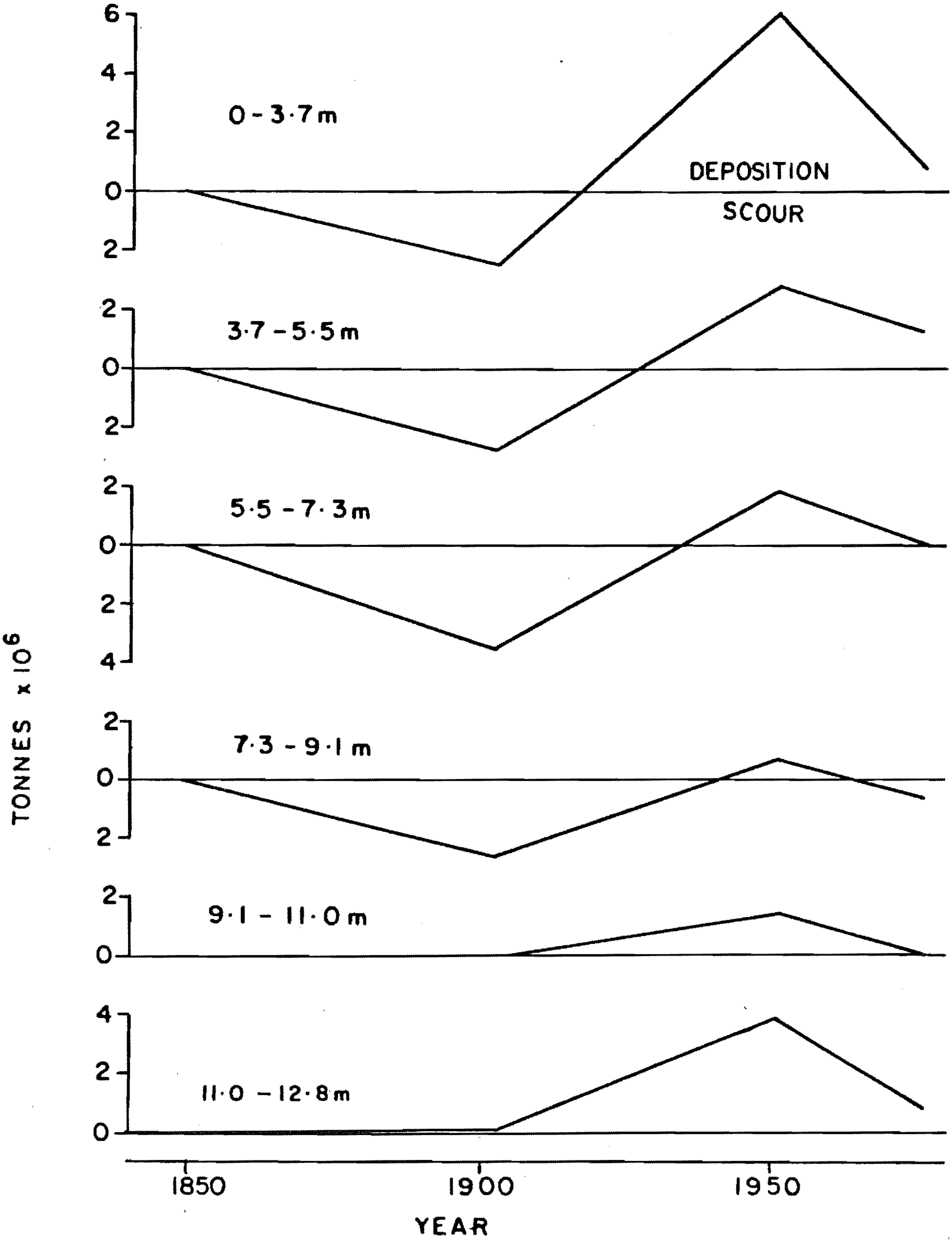


Figure 3.3 Graphs of rates of sediment accumulation for various harbour depths with respect to the 1849 contours.

and erosion were operating at constant average rates between surveys. Consideration of average rate figures in Table 3.1 reveals substantial variation over time, so that more short term variations in erosion and sedimentation may have occurred between the surveys than the graphs depict. However, the graphs do provide effective illustrations of longer term trends.

Secondly, the technique presumes spatially uniform sedimentation patterns in the area between two contours under consideration. Again this is incorrect. Brodie (1955) found the harbour had deepened to the east and west of Quail Island but had become shallower to the southeast of the island. All these regions fell within the area between two contours surveyed in this study, although Weggel's technique did not show the differences in scour and deposition between the contours selected. Similarly, both Brodie (1955) and Bushell and Teear (1975) found areas of deposition, scour, or no change in the region between Charteris Bay and Purau Bay on the southern side of the harbour which fell within the area between the 5.5 and 7.3 m depth contours examined. However, in the context of this study the differences in depths between scour and depositional regions in the same survey areas was minimal.

The analysis technique has established general temporal and spatial trends for sedimentation within the harbour. In so doing it has enabled the "historical" stability of the harbour to be analysed. Figure 3.2 demonstrates that while the harbour has been relatively stable in the longer term from 1849 to 1976, there have been considerable variations in sedimentation over shorter periods. Clearly the harbour has not been in a state of equilibrium since it was first surveyed in 1849. However, the contemporary state of equilibrium is more difficult to assess. Although the comparison between the 1951 and 1976 charts shows a greater degree of stability than prior to 1951, this may represent a short term state, and more information is required to interpret the contemporary harbour conditions. Therefore it is now appropriate to consider the nature of the sediments, their precise distribution within the harbour, and the directions of transport through the harbour and from erosional to depositional areas.

3.2 SEDIMENTS

3.2.1 Sampling and Textural Analysis

Eighty-six samples were collected from within the harbour and beyond the entrance for approximately 1 km. Figure 3.4 shows these sites. Characteristics of the sediments are listed in Appendix 1 and Table 3.2. Of the samples,75 were from the harbour bed, three from stream beds at Governor's Bay, Head of the Bay, and Purau Bay, and eight were from beaches around the harbour perimeter. Stream bed and beach samples were collected by hand; samples one to nine, in the intertidal zone, as short cores up to 1 m long using 50 mm PVC tubing; and sea bed samples using a small pipe dredge (105 mm diameter by 300 mm in length) lowered from a launch, which obtained a disturbed surface sample. All samples were placed in labelled plastic bags and taken for analysis to the geomorphology laboratory in the Geography Department, University of Canterbury. Position fixing for all sediment sampling and sedimentation experiments was

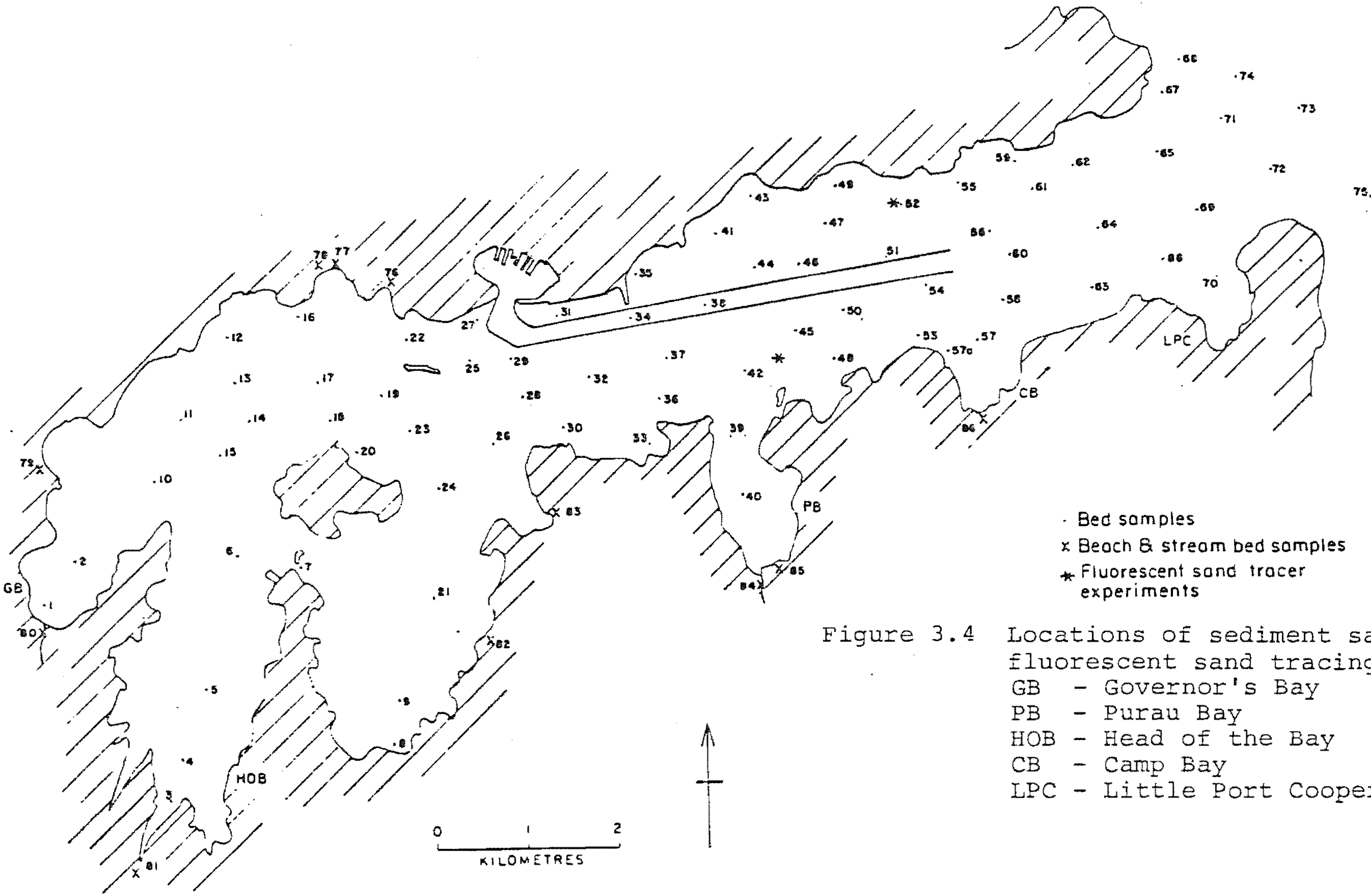


Figure 3.4 Locations of sediment samples and fluorescent sand tracing experiments.
GB - Governor's Bay
PB - Purau Bay
HOB - Head of the Bay
CB - Camp Bay
LPC - Little Port Cooper

accomplished using sextant and compass bearings to the numerous harbour and channel markers.

In the laboratory, cores were halved and stored after samples had been removed from the top of each. All samples were spread on newspaper and left for several days to air-dry. Because of the high content of fine material the dried sediments formed hard masses which were broken into small lumps. From these, sub-samples of approximately 60-100 g were removed by hand and wet sieved through a 0.0625 mm sieve using distilled water. All shells were removed from sea bed samples and shells larger than gravel size were removed from beach samples. Sample 7 was the only bed sample containing visible shell material. Visible organic matter was also removed from all samples. Coarse fractions were oven dried overnight at 100^{o}C following wet sieving, while fines were transferred to 1000 ml flasks for hydrometer analysis using the method outlined in Carver (1971). Prior to filling each flask with distilled water, fines were transferred to an aluminium container, 50 ml of calgon were added to prevent flocculation, and the sample was stirred vigorously for five minutes in a "milkshake" machine.

Coarse fractions were split to obtain approximately 30 g and then sieved on a mechanical shaker for 15 minutes at 0.25 ϕ intervals ($\phi = -\log_2$ (grain diameter mm)) down to 0.0625 mm. Fractions from each sieve were inspected beneath a microscope for shell content and aggregate. These were visually assessed as a percent content and where aggregate was present the fraction sample weight was corrected accordingly. Half the beach samples contained high shell content and were treated with a 10% solution of concentrated HCl. However, problems were encountered with drying these samples and they were not subject to size analysis. Remaining beach samples were sieved.

Subsequently straight line grain size curves were drawn on probability graph paper, and the textural parameters of mean grain size, sorting, skewness, and kurtosis calculated for each sample after Folk (1974). These data are presented in Appendix 1.

Bed sample composition is similar throughout the harbour, differing largely in sand content. Mineralogy consists of Quartz, Plagioclase Feldspar, minor Clinopyroxene, and minor and variable amounts of illite, montmorillonite, chlorite, and vermiculite clays (Crampton, 1985; Weaver, 1982). Weaver states;

> The Quartz and possibly some Feldspar are derived from loess. The assemblage Plagioclase plus Clinopyroxene represents Lyttelton volcanic detritus and the clays are weathering products of this material. The sediments sampled are not primary volcanic material but are a mixture of loess and volcanic detritus (colluvium).

Stream bed samples comprise fine silt and clays at Governor's Bay and Head of the Bay, and a mixture of coarse sand to clay sized material at Purau Bay. Beach material varies from gravel to fine sand, frequently with a high content of shell hash. Table 3.2 outlines brief descriptions of the beach and harbour sediments.

3.2.2 Distribution of Mean Grain Size, and Sorting

Uniformity of bed sediments in terms of mineralogy and textural parameters meant that the only concise means of distinguishing between samples was through percent content

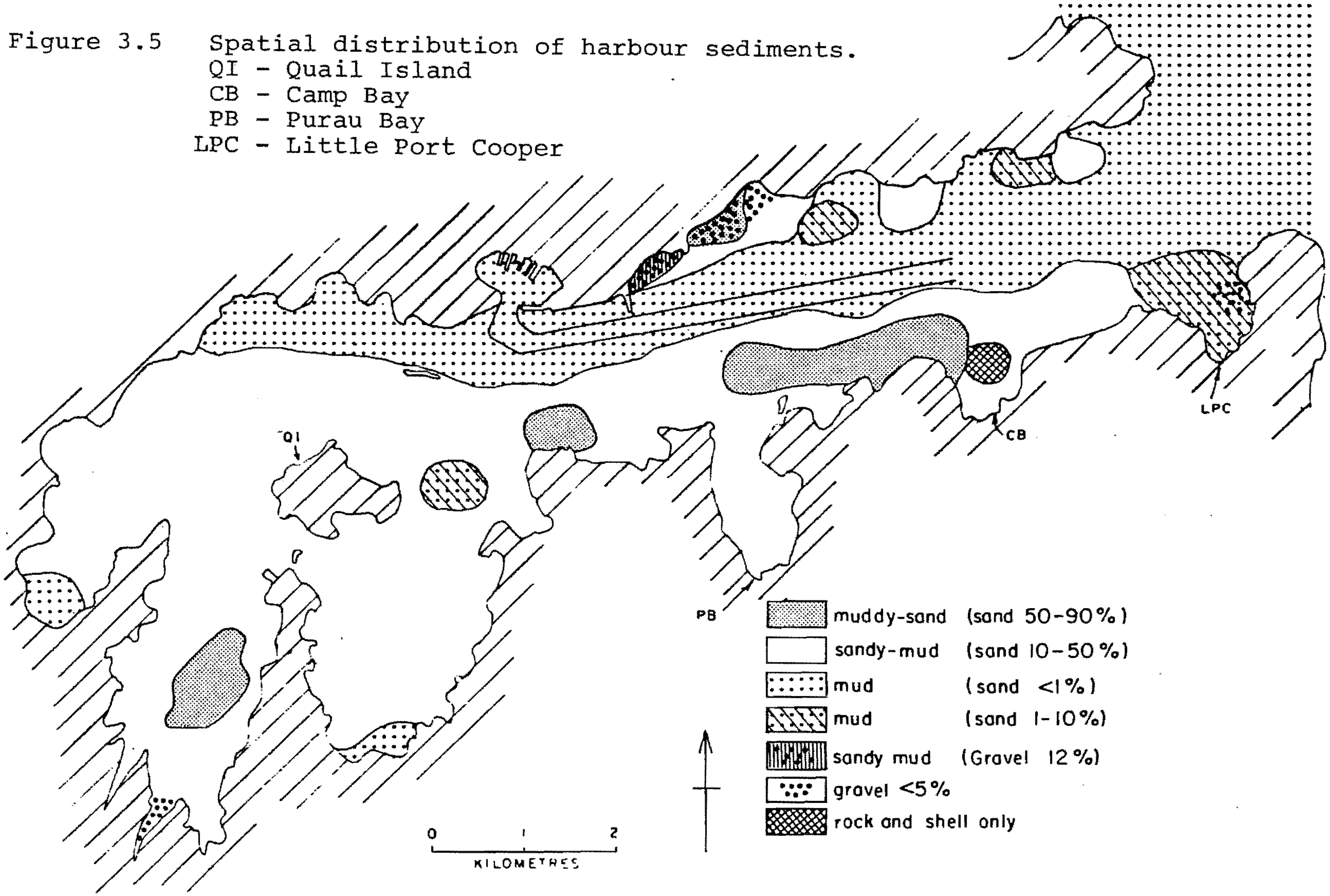
Table 3.2 Description of sediments grouped in terms of environmental conditions

Location	Sample* Nos.	Sediment Type	Verbal Description	Probable Source
Harbour Bed	All harbour bed samples excluding those below and 57.	Mud and sandy-Mud	Blue-grey. Poorly to very poorly sorted.	Colluvium
Harbour Bed	5,30,41,42 53,57a.	muddy-Sand	Brown-grey. Poorly sorted.	Colluvium
Harbour Bed	48	Sand (>80%)	Brown-grey. Well sorted.	Colluvium
Governor's Bay Stream Bed	80	sandy-Mud	Blue-grey. Very poorly sorted.	Colluvium
Head of the Bay Stream Bed	81	Mud	Blue-black. Very poorly sorted.	Colluvium
Purau Bay Stream Bed	84	sandy-Gravel	Brown. Very poorly sorted.	Colluvium and Volcanics
Purau Beach	85	Sand	Grey. Moderately well sorted.	Colluvium
Cass Beach (1)	78	sandy-Gravel	Poorly sorted.	Volcanics
Cass Beach (2)	77	Sand	Brown-grey. Well sorted.	Colluvium
Governor's Bay (Jetty)	79	sandy-Gravel	Poorly sorted.	Volcanics

* Sample 57 contained rock and shell only.

Samples 76, 82, 83 and 86 comprised sand with high contents of shell hash and were not subjected to textural analysis.

Figure 3.5 Spatial distribution of harbour sediments.
QI - Quail Island
CB - Camp Bay
PB - Purau Bay
LPC - Little Port Cooper



by weight of sand. Figure 3.5 portrays the areal distribution of surface sediments in this manner.

As can be seen, with the exception of a broad band of sandy sediment between Camp Bay and Purau Bay, the harbour contains two general sediment classes; sandy-mud and mud. Sandy-mud (10-50% sand) is prevalent at the head of the harbour, mud (<10% sand) at the entrance, and between Quail Island and Little Port Cooper the harbour is divided evenly and longitudinally, into zones of mud and sandy-mud. Along the entire length of the harbour sediments on the northern side are predominantly fine muds while those to the south are coarser sandy-muds and muddy-sands, with a sharp demarcation between the two. Only at the very entrance where mud extends uniformly across the harbour is this demarcation between coarse and fine material absent. Figure 3.6 illustrates the tendency for sand to accumulate at the head of the harbour and on the south side only, while Figure 3.7 shows the ubiquitous nature of clay sized material. In both cases the percentage contour lines extend lengthwise along the harbour suggesting movement of material across the harbour. Regions of maximum sand and clay content occur respectively on the southern shoreline, and down the centre of the harbour, along and slightly north of the channel line. However, bathymetric data in section 3.1 point to erosion of material in the central harbour area, (sand and mud), and deposition of material at the head, (predominantly sandy-mud) and entrance (mud). The directions of transport implied by bathymetric data and percent content contours are therefore contrary, so that a degree of caution should be exercised in interpreting flow regimes from sedimentary data in Lyttelton Harbour. This is despite the fact that the distribution of surface sediments has

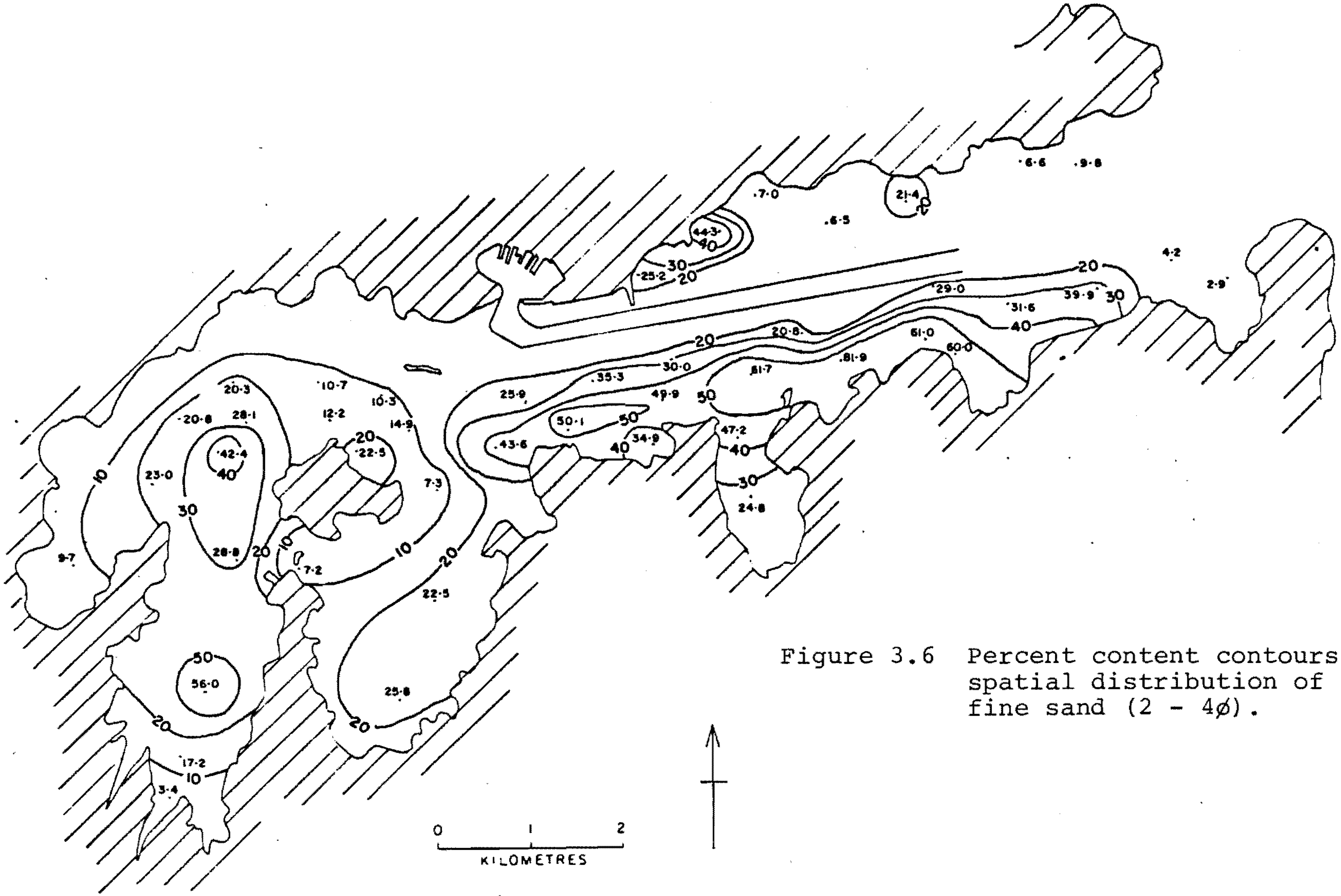


Figure 3.6 Percent content contours showing spatial distribution of fine to very fine sand (2 - 4ø).

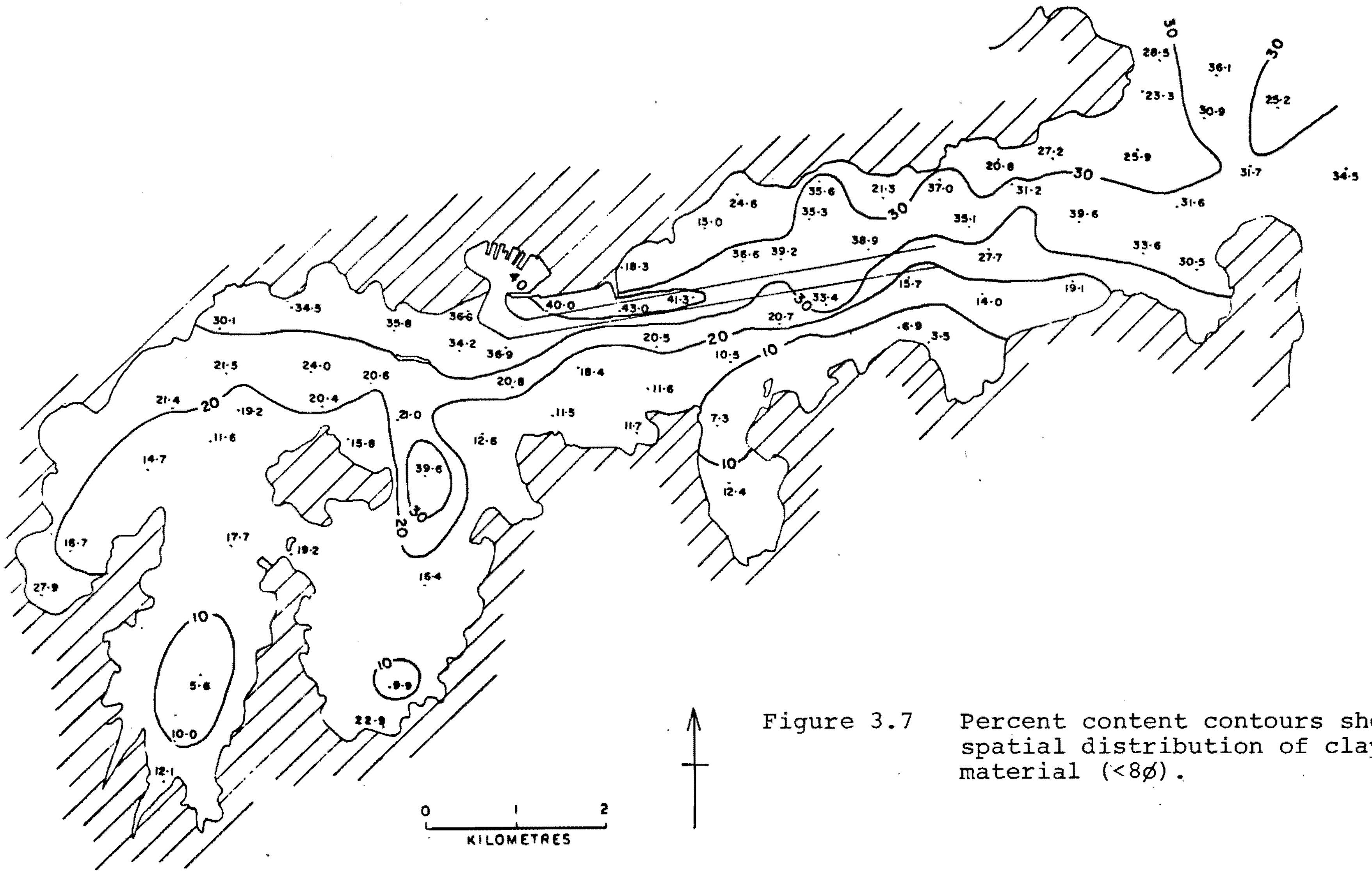


Figure 3.7 Percent content contours showing spatial distribution of clay size material (<8ϕ).

remained very much the same since 1849 (Brodie, 1955; Bushell and Teear, 1975).

Mean grain size contours shown in Figure 3.8 are also parallel to the longitudinal axis of the harbour indicating, if it is accepted that sediment transport can be inferred in a direction normal to grain size contours, that sediment transport is across rather than along the harbour. Certainly in respect of sand sized material such an inference is ruled out here due to the total absence of sand along the centre of the harbour, particularly in the channel.

Lyttelton Harbour is atypical of other New Zealand harbours where grain size contours are generally normal to the longitudinal axis and to ebb and flood flows; e.g. Whangarei (Millar, 1980); Raglan (Sherwood, 1974); Wellington (Carter, 1977; van der Linden, 1966). Contours in Lyttelton do however become normal to the longitudinal axis at the entrance, outside the harbour side boundaries.

Inclusive Graphic Standard Deviation (σ_I - the sorting coefficient) is a measure of the range of sizes in a sample, although quite different to the notion of sediment "grading" common in engineering usage. The narrower the range the better (lower) the sorting value, and it is generally assumed that selective transport of sediments results in better sorting (Allen, 1977; Kirk, 1980).

All sediments in Lyttelton are poorly sorted ($\sigma_I > 1.0$) with the exception of samples 48 and 57a which are well sorted and moderately sorted respectively. Both are sandy sediments. The degree to which various sediments are poorly sorted is more apparent from examination of Figure 3.9 which shows that sorting improves at both ends of the mean

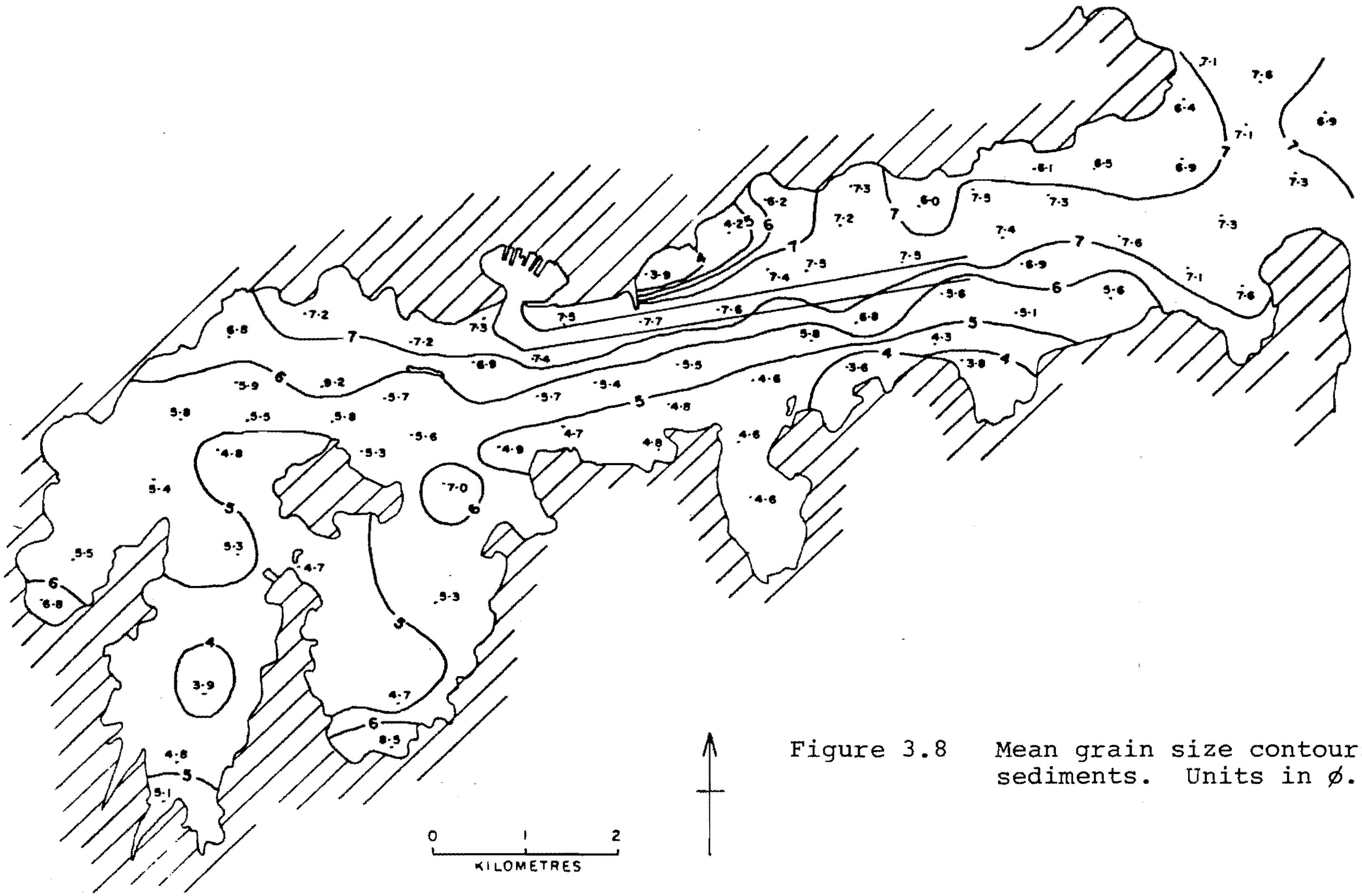


Figure 3.8 Mean grain size contours for bed sediments. Units in ø.

grain size range as sediments become coarser than about 5.5 ϕ and finer than about 7 ϕ.

Folk (1974) states that sorting depends on three major factors: (1) the size range of the material supplied to the environment; (2) the type of deposition - whether sediment is "spread" continuously or "dumped" rapidly; and (3) the characteristics of currents, or hydraulic critera. Folk (p.4-5) observes that;

> ...sorting is strongly dependent on grain size... Following from fine sand into finer sediments, the sorting worsens so that sediments with a mean size of 6 to 8 ϕ (fine silts) have the poorest sorting values, then sorting gradually improves into the pure clay range (10 ϕ).

This is likely to apply to Figure 3.9 where sediments coarser than 5.5 ϕ contain fine sands and coarse silts (probably already presorted by loessial history prior to entering the harbour), and finer than 7 ϕ there is an increasing pure clay content in the samples. Between 5.5 and 7 ϕ there will be mixtures of sands, silts and clays, and mixtures by definition will be more poorly sorted than either of the "end member" sediments.

While sorting values overall are consistently poor, the degree of 'poorness' can be classified using Folk's (1974) verbal descriptions and these are illustrated spatially in Figure 3.10. It is likely that the two areas of well sorted and moderately sorted sediments on the southern side between Purau Bay and Camp Bay are due to grain size considerations and are a function of material supplied to the environment at those locations. Sand sized material predominates in this region. Elsewhere in the harbour, small variations between poorly and very poorly sorted sediments probably reflects a combination of grain size and hydraulic factors. However, while transport selectivity on the basis of sorting

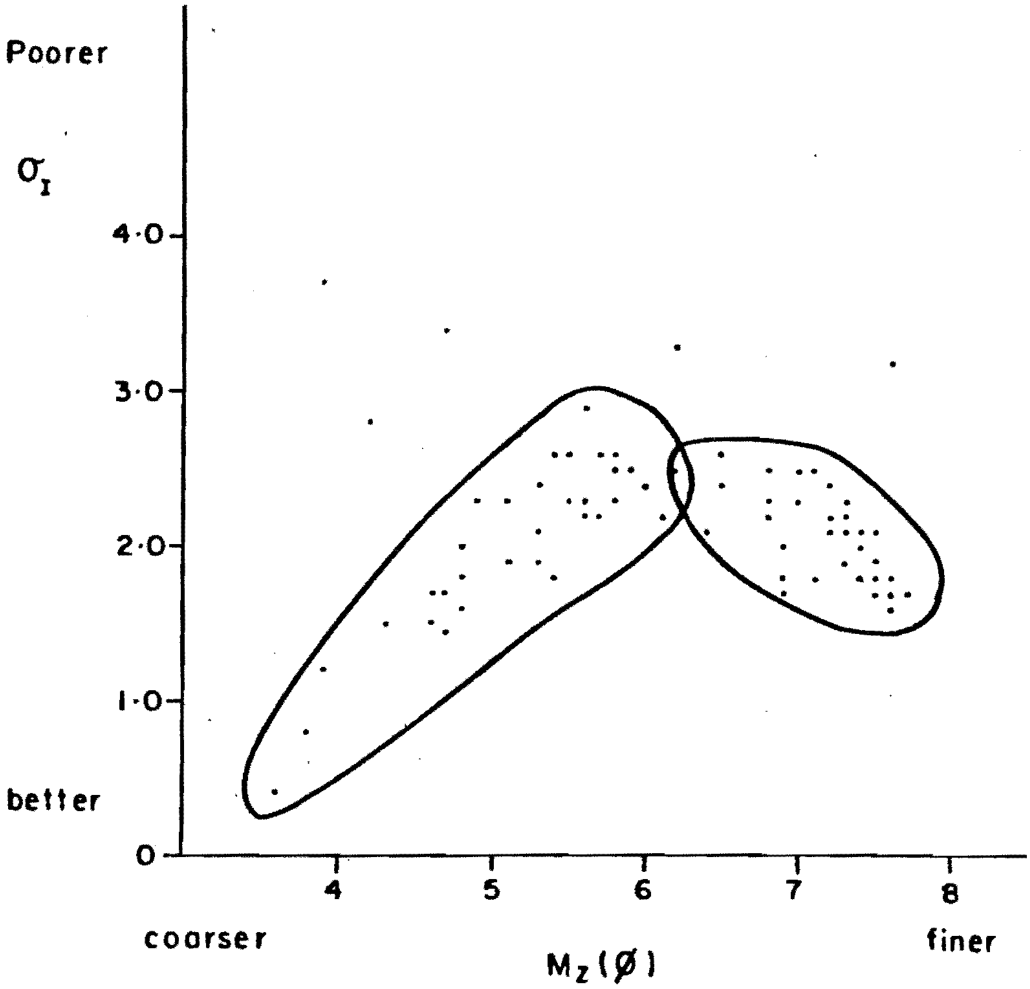


Figure 3.9 Graph of sediment sorting vs mean grain size.

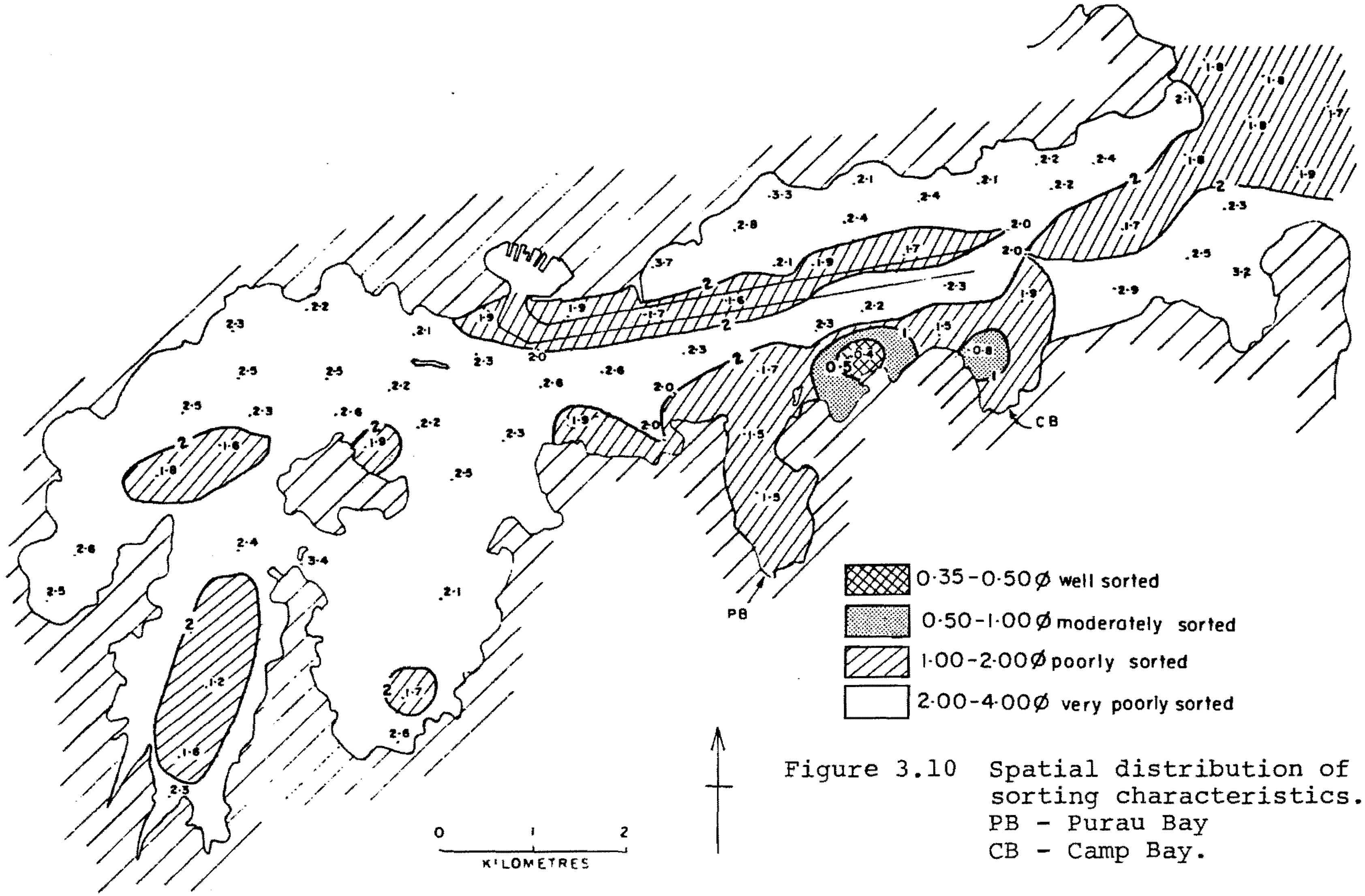


Figure 3.10 Spatial distribution of sediment sorting characteristics.
PB - Purau Bay
CB - Camp Bay.

is relative, the small extent of variation in sorting between samples renders valid transport inferences from these data unlikely.

3.3 SEDIMENTATION PATTERNS

3.3.1 Rollability Analysis of Sand

Rollability is a functional measure of sand grain shape properties derived from the rolling behaviour of sand grains through an inclined, smooth-walled cylinder. Traditionally grain size has been used, more than any other parameter, to interpret transport processes from sediments and yet traditional measurement techniques allow at best a somewhat indirect relationship between grain size and the physical processes enacting erosion, transportation, and deposition. Winkelmolen (1982) observes that the numerical value of grain surface (as in the surface area to volume ratio) is important in whether or not a certain weight can be transported under given conditions. Since shape is the unique parameter controlling surface area of volumes, selection according to shape in transport becomes increasingly important with increasing grain size. Grain size is unsatisfactory for hydraulic interpretation as much of the size distribution in a given sample may reflect previous environments, or the source as mentioned in the previous section on sorting. A property like rollability, measuring shape and surface area to volume ratios, will therefore reflect less of the history of a sample and more of the contemporary environmental conditions which it is under. Further to this, Winkelmolen (1969b; p.304-305) states:

> Shape selection becomes especially interesting in those cases where the available sizes do not reach the competency of the transport processes and where deposition occurs as a result of deficiency in capacity. Size then largely fails as a criterion, but shape selection is still active. This is the more so since under such conditions there can be a continuous particle exchange between the transported load and the bottom sediment resulting in the gradual rejection of the best rollable shapes in transport.

In order to measure sand grain shapes to interpret sediment transport, the "Rollability Apparatus" was developed by Winkelmolen (1969a). Kirk (1980) comments that "...considerable improvements in both measurement technique and in hydrodynamic interpretation have been made through the introduction of the Rollability Apparatus....".

Analysis, undertaken in the geomorphology laboratory, Geography Department, University of Canterbury, involved measuring the rolling behaviour for all sieve fractions containing 0.4 g or more of sand. This involved 49 of the 86 samples, which, sieved at 0.25 ϕ intervals gave 228 fractions containing 0.4 g of sand to be rolled. Analysis was applied to sand sizes on 17 0.25 ϕ sieves between 1.0 mm and 0.625 mm.

The instrument separates various sand grain shapes according to their rolling times through a slowly rotating, smooth-walled cylinder inclined at 2.5°. As grain size is held relatively constant by the narrow sieve intervals, and density variations in Lyttelton Harbour sediments are slight, the primary factors influencing rolling times are grain shape, roundness and texture. While particles roll through the cylinder, less equal, flatter, and rougher grains are carried higher up the cylinder wall to greater friction angles than are more equant, rounder, and smoother grains which emerge from the lower end of the cylinder first having travelled a shorter overall distance. All grains follow a spiral path with a spectrum of shapes being obtained both in the axial direction, as the particles migrate towards the end of the cylinder, and in the lateral direction (Winkelmolen, 1971). The grains pass through a funnel and are collected on an electromechanical microbalance from where a cumulative curve of arrival, or rolling times, is recorded on a strip-chart for each sieve fraction. From these curves the medium rolling time was determined and relative rollability values computed by expressing the rolling time for a given sieve fraction as a percentage of the average for the size class to which it belonged. These are expressed in a positive or negative sense such that positive values represent better (faster) rollabilities and negative values poor rollabilities. A mean value was then calculated for each sample from the relative rollability values of each sieve fraction in that sample.

The purpose of performing these calculations was to establish locations within Lyttelton Harbour where relatively more rollable, and relatively less rollable sand grains are concentrated. This allows determination of sediment sources and sinks, and can identify major transport vectors between them. Positive rollability values represent fast rolling times, or more equal, rounded, and smooth grains less susceptible to transport. Thus locations with positive values represent sediment lag deposits or sources, inasmuch as grains susceptible to transport have been removed, or are not deposited, and locations with negative values represent receiving deposits. Two points should be noted however. Firstly, the technique provides no data on sediment transport rates or quantities, and secondly, the analysis is relevant only in terms of zones of relatively more or less rollable grains. Therefore the concern lies with spatial variability within the survey area rather than with the actual shapes of individual grains or with their absolute rolling times.

Of the samples analysed, few contained more than three or four sieve fractions with 0.4 g of sand, and only beach and stream bed samples contained sand sizes coarser than 2.0 ϕ. It was found that the most sensitive indicators of sedimentation processes from these data were the average relative rollability values for whole samples, and relative rollability values for very fine sand (0.0625 mm) fractions. Accordingly only these data are presented here and are set out in Table 3.3. As can be seen the sediments display a wide range of average relative rollability values, (from -5.69% to +5.95%), indicating considerable variations from place to place in sand grain shape properties.

In Figure 3.11 a contoured distribution of average relative rollability values shows three distinct zones in sedimentary process terms. On the south side of the harbour between the port and Camp Bay sediments represent predominantly lag deposits, strongest between Purau Bay and Camp Bay. Then at either end of the harbour strong "sinks" or receiving deposits exist within the entrance and around Quail Island. A number of localised lag deposits exist, notably on the northern side, at Quail Island, and in Charteris Bay, but effectively the harbour sediments are receiving deposits apart from the main source area on the southern side. Implications which can be drawn from this pattern include:

(a) Sand sized material is being transported bidirectionally up and down the harbour on the southern side.

Table 3.3 Selected Relative Rollability Values

Sample No.	Av. Relative Rollability (%) for Whole Samples	Rel. Rollability (%) for 0.063mm Fraction
2	-1.53	-0.69
3	-1.89	-1.74
4	-1.74	-0.69
5	-2.51	+0.88
6	-2.70	-0.69
7	-5.69	-4.89
9	-2.26	-0.69
10	-3.59	-1.74
11	-2.87	+0.36
13	-1.94	-1.74
14	-2.20	+0.36
15	-1.56	-0.69
17	-0.66	+1.40
18	-1.39	+0.36
19	-1.70	-0.69
20	+0.13	+1.40
21	+1.48	-0.17
23	-1.14	-0.69
24	-2.45	-2.27
26	-0.32	+1.40
28	+0.11	+0.36
30	+0.18	+1.40
32	+0.77	-0.17
33	+0.58	-1.22
35	+1.13	+1.93
36	-1.04	+1.93
37	-2.42	+1.40
39	+1.98	+0.36
40	+0.37	-0.17
41	-1.02	-0.69
42	+1.24	+1.93
43	-0.61	-0.17
45	+1.86	-0.69
47	-1.70	-0.17
48	+1.84	+1.93
52	+1.14	+1.40
53	+1.55	+1.40
54	+1.75	-0.69
57a	+0.90	+2.45
58	-0.39	-0.69
59	-1.88	-2.27
62	-2.11	-0.69
63	-0.16	+1.93
66	-2.42	-2.79
70	-1.35	-0.69
78	+5.95	- *
80	-1.75	+1.40
84	-1.14	+3.50
85	+4.84	-

* Samples did not contain very fine sand fractions

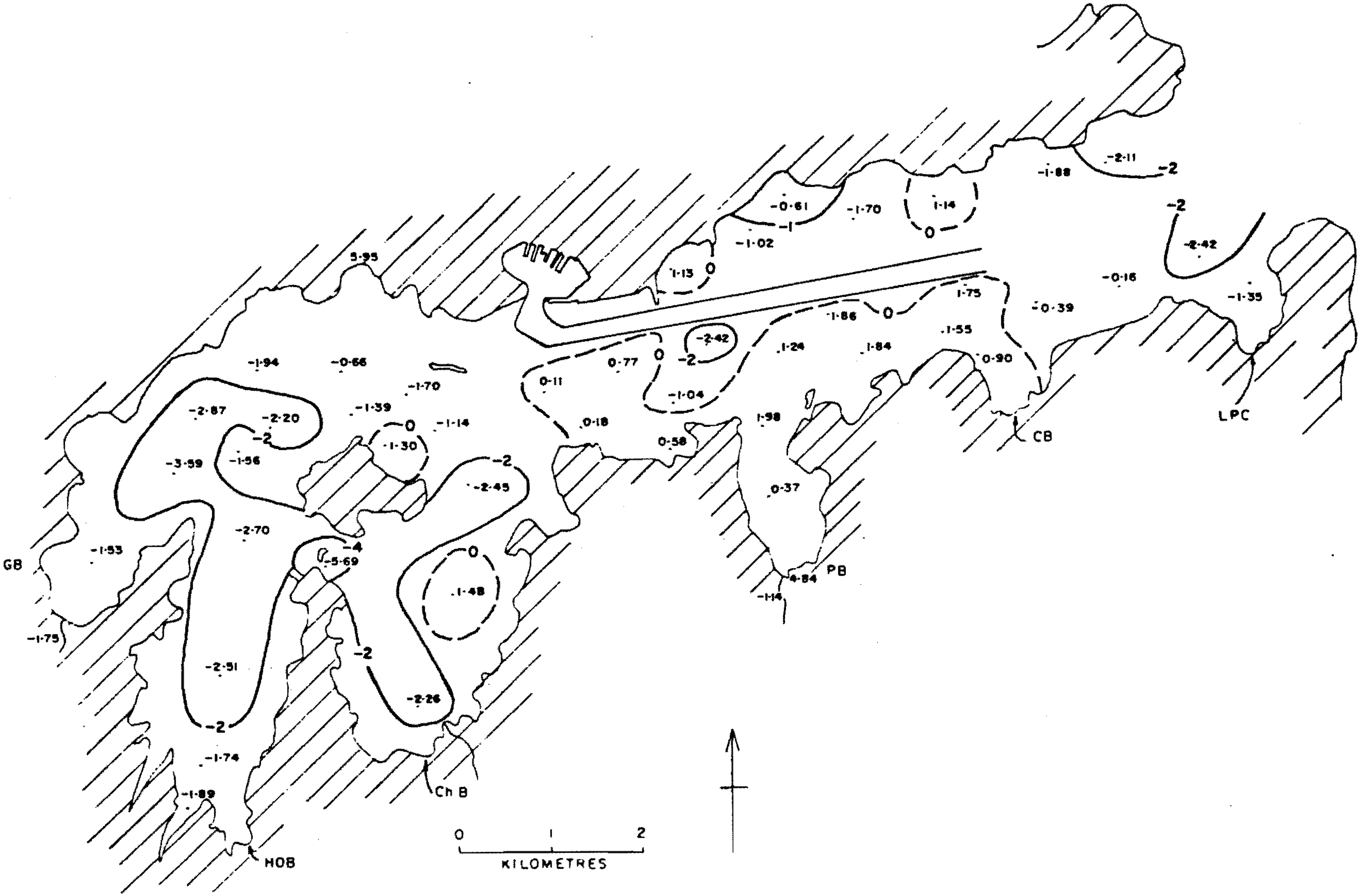


Figure 3.11 Average relative rollability (%) distribution for whole samples.
GB - Governor's Bay HOB - Head of the Bay ChB - Charteris Bay
PB - Purau Bay CB - Camp Bay LPC - Little Port Cooper

(b) Sand is transported down harbour on the northern side east of the breakwater.

(c) Sand is accumulating both at the head of the harbour and at the entrance to the harbour. There is also a strong receiving region in the centre of the harbour, between Purau Bay and the breakwater, which interrupts the continuity of a long 'source' region extending along the southern side of the harbour.

(d) No transport vectors can be drawn across the harbour from north to south or vice versa because of the absence of sand in the channel and its surrounds.

Additional information can be obtained from analysis of relative rollability values for individual sieve fractions, in this case very fine sand (0.0625 mm), depicted in Figure 3.12. Interpretation of these data are as follows:

(e) Very fine sand is not accumulating in the region between the breakwater and Purau Bay, and while strong sinks for this size fraction occur at the entrance to the harbour, they are greatly reduced in size compared to the sinks for samples as a whole.

(f) The strongest 'source' area for very fine sand is at Camp Bay and transport occurs bidirectionally from this location. The source area for very fine sand extends almost the entire length of the harbour on the southern side, from Little Port Cooper to Governor's Bay and into the Head of the Bay which is a sink on values for the samples as a whole.

It is worthwhile noting at this juncture, the similarity between these data and the historical bathymetric

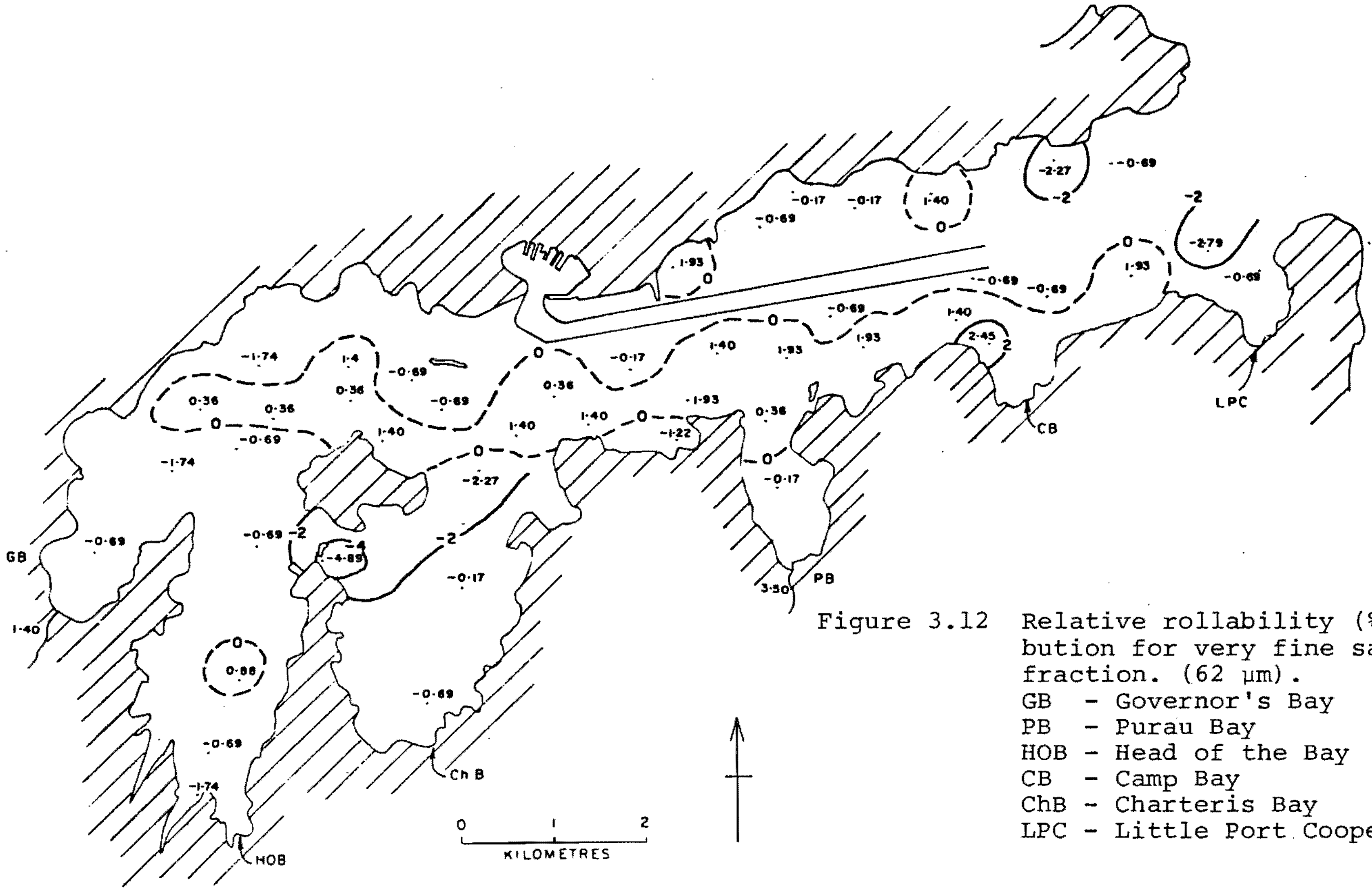


Figure 3.12 Relative rollability (%) distribution for very fine sand fraction. (62 μm).
GB - Governor's Bay
PB - Purau Bay
HOB - Head of the Bay
CB - Camp Bay
ChB - Charteris Bay
LPC - Little Port Cooper

data. Figure 3.2 shows that since 1951 deposition has occurred at the head and entrance of the harbour with erosion occurring between the two. This pattern is emulated in the long term graph showing deposition and scour from 1849 to 1976. It is also emulated by the relative rollability data which show a virtually identical pattern of deposition and erosion under contemporary processes. It is apparent that long term sedimentation patterns are continuing under the present hydrodynamic regime, although as Figure 3.2 illustrates, there have been short term variations to the pattern.

The difference between the two diagrams, Figures 3.11 and 3.12, is in the presence or absence of coarse sediments; one having the entire sand sample and the other having only very fine sand. Since source areas, bounded by zero contour lines on the diagrams, represent zones where maximum entrainment or at least deposition of the particular sediment occurs, a high level of interpretation can be gained from the two diagrams in conjunction. Four major points can be made:

(1) The hydraulic capacity for entrainment in the upper harbour, west of the breakwater, is considerably greater for very fine sand than for coarser particles, and the relative strengths of sinks for finer sediments are less. Very fine sand is actively removed from an elongated region to the north of Quail Island, and in the centre of the Head of the Bay. Coarser sand is being eroded from Charteris Bay.

(2) In general, the upper harbour acts as a large sink for sand sized material. Accumulation of coarser material is particularly marked to the west of Quail

Island and in Governor's Bay, Head of the Bay, and Charteris Bay. Very fine sand is also deposited in these areas but to a lesser degree. The main sink for very fine sand is to the south east of Quail Island, at the northern end of Charteris Bay.

(3) Strong sinks at the entrance to the harbour demonstrate sand accumulation in this area. However, consideration of the two diagrams reveals that whole sample relative rollability values show comparable sinks on both sides of the entrance, while very fine sand is being deposited almost entirely on the south side only. It is concluded from this that there is an imbalance in the entrance hydraulics which prevents significant deposition of fine sand on the northern side of the entrance.

(4) The absence of sand sized material in the centre of the entrance and the centre of the harbour indicates that either sand does not reach these areas to be deposited, or that it is selectively transported away from these regions. Comparison of the relative rollability figures with Figure 3.10, the spatial distribution of sorting values, shows a correlation between regions lacking sand and regions with slightly better sorting indicative of selective transport processes. However, well sorted, sandy sediments between Purau Bay and Camp Bay coincide with the strongest 'source' zones indicated by relative rollability values, and it is more likely that the source of sand sized particles is in this region and currents transport bidirectionally along the southern side of the harbour. Sand on the northern side is probably derived from the

cliffs in that area, especially a quarry above the breakwater and Battery Point, and moves down-harbour from the breakwater.

Thus, rollability analysis has identified two apparently independent sand transport systems on either side of the harbour, with a zone of virtual sand exclusion in the centre. There was no indication of lateral flow or mixing between the two systems, but an attempt to verify this, and sand transport directions along the harbour, was made utilizing tracer material.

3.3.2 Fluorescent Sand Tracing

Ideally, because of the extremely fine sediment within Lyttelton Harbour, radio-active tracers would have been used to examine sediment transport. However, the expertise and equipment to support such a technique were unavailable and fluorescent, dyed sand tracing was used as an alternative.

One hundred and twenty kilograms of fine sand was dyed with the fluorescent orange pigment K459 (obtainable from Morrison Printing Inks and Machinery Ltd, 351 Selwyn Street, Christchurch) according to the technique outlined in Hastie (1983). When dyed the average grain size of the sand used was 0.177 mm, slightly coarser than very fine sand, and 0.133 and 0.161 mm coarser than the mean grain sizes of bed sediments at the southern and northern tracer sites respectively. The two sites (Figure 3.4) were marked with buoys and 60 kg of dyed sand poured, from drums, onto the sea bed by divers at each site. The sand was spread by hand in a 2 m radius to remove the mound which would have been more readily eroded by currents. Due to weather deterioration the first sampling run was delayed until eight days after the release of sand. Hastie (1983; p.198) observed that mixing of dumped sand grains into the bed took up to 10 days and that long term sediment transport rates should be based on measurements made after this time. Theoretically then, the lapse of eight days prior to sampling should not have presented undue problems.

Initial sampling consisted of two divers pushing 30 x 5 cm PVC cores into the bed at the dump site, and at 10, 20, 30, 40 and 50 m from the dump site. Sampling intervals were identified from knots tied in a rope stretched along the sea bed. Four runs were made at each site along four compass bearings; SW, NW, NE, and SE.

Samples were displaced from the cores into labelled plastic bags on the launch and inspected for tracer grains using an ultra-violet lamp. No tracer was found at either site and divers resampled randomly around each buoy in a radius of up to 200 m. Samples were returned to the laboratory and inspected under an ultra-violet lamp but again no tracer was found. It was concluded that the tracer had been lost.

Two possible causes for the loss of tracer can be put forward. Firstly, it could have been transported away from the dump site, or secondly, it could have been buried. The latter cause is considered most likely at the northern site where bed sediment comprised mainly fine mud and was thus unsuitable for an experiment of this form. At the southern site, near Purau Bay, bed sediments were sandier and the first mentioned reason for tracer loss is preferred.

Cores removed held predominantly sandy material in which any tracer would have been readily identifiable. No wave data were obtained during the experimental period. However, considering the conditions following the sand release it must be concluded that storm wave effects induced rapid transport of sand from the tracer site. Wave induced currents and their effects are discussed in chapter five.

It must be reiterated here that the above experiment, and rollability analysis, apply only to sand-sized material which comprises a minor portion of harbour sediments. The ubiquitous nature of clay-sized material throughout the harbour and the strong, fine-skewness of most samples required an investigation into the transport and distribution of muddy sediments.

3.3.3 Suspended Sediment and Fluid Mud

Referring to the gentle gradient of 1 in 1,000 of the harbour bed along its 14 km length, Bushell and Teear (1975; p.54) comment:

> It is doubtful whether such a degree of flatness can exist in nature in any other state than semi-fluid or fluid and indeed all tests and investigations so far made confirm that the bed of the harbour at times exhibits the properties of a fluid.

Such bed fluidity requires the presence of unconsolidated surface sediment with a high water content, or 'fluid mud'. Fluid muds are documented in a number of estuaries; the Thames (Inglis and Allen, 1957), the Chao Phya (Allersma *et al*. 1966), San Francisco Bay (Einstein, Asce, and Krone, 1961), the Gironde (Allen *et al*. 1976) and the Maas and Mersey (Kirby and Parker, 1977). However, little is known about their formation, dispersal and longitudinal transport, or importance in estuarine sediment budgets (Officer, 1981).

Accordingly, a survey of near-bed suspended sediments was conducted in an effort to ascertain the presence and locality of fluid mud deposits and to examine the manner of transport and dispersal of fine-grained sediment within the harbour.

To this end a suspended sediment sampler, shown in Figure 3.13, was designed and constructed to collect 12 simultaneous samples between the bed, and 1 m above the bed at approximately 8.5 cm intervals. The sampler was diver operated, having first been lowered by rope, oriented into the current by reference to a float tied to the top, and allowed to settle under its own weight on the bed. Corks were removed from the intake nozzles on the 1 litre bottles and the tap opened at the top of the sampler allowing air to bleed simultaneously from all 12 bottles. As the plastic bottles were naturally compressed to equilibrate internal and external pressures on the sea bed, there was minimal water intake when the corks were removed prior to the air tap being opened. Two divers were required to operate the sampler.

Large steel weights were tied to the sides of the sampler to enable surface water tension to be broken as the 12 bottles were naturally buoyant. It was under this weight that the sampler settled to the "bed", defined for the purposes of this survey as the point where the sampler came to rest. In this way several variables were sampled; the degree of bed sediment consolidation; suspended sediment concentrations in the water column up to 1 m; and the

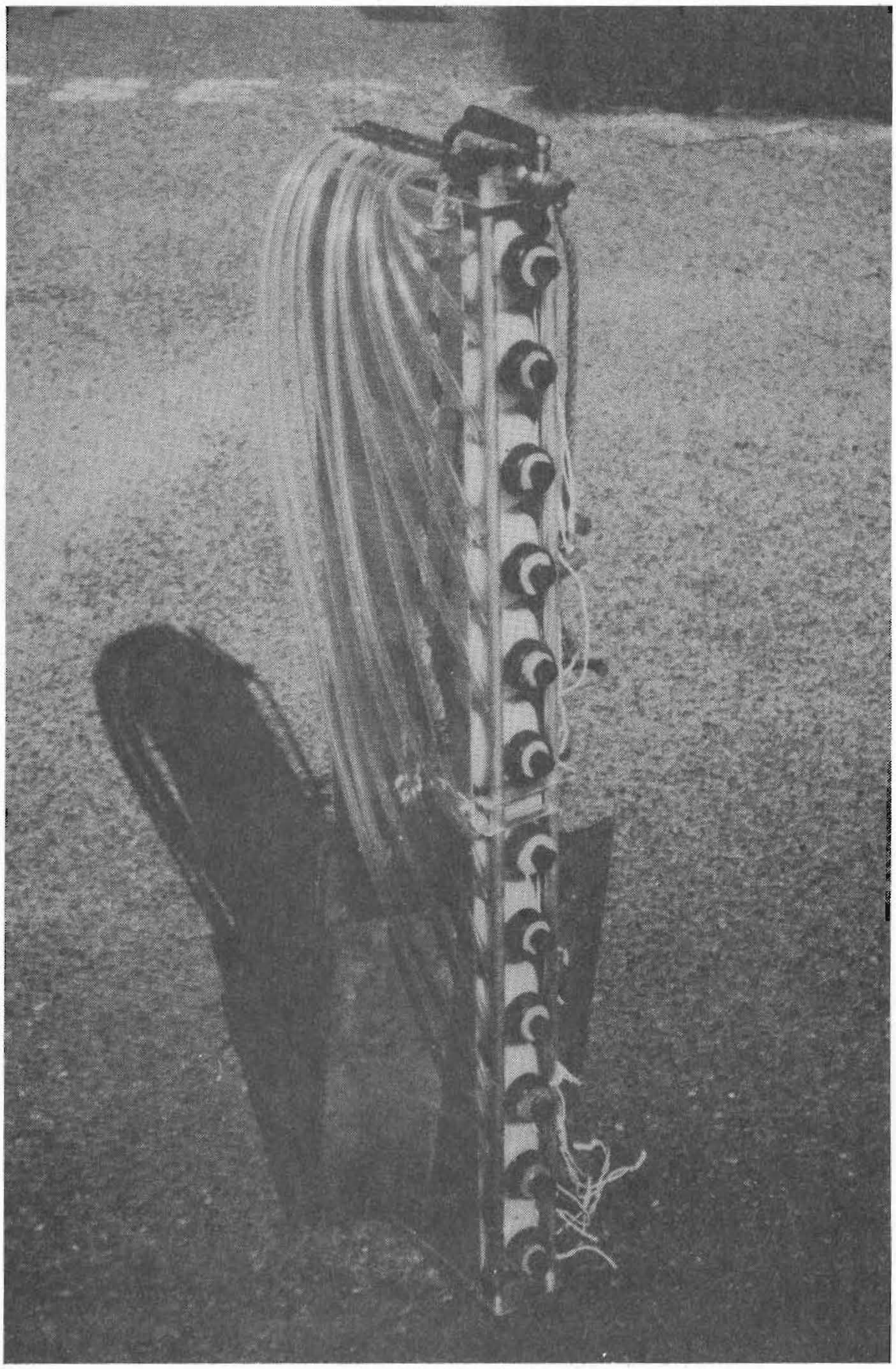


Figure 3.13 Suspended sediment and fluid mud sampler. The sampler is 1 m high. Air is bled simultaneously from the 12 bottles using the valve at the top of the sampler.

presence and concentration of near-bed fluid mud. Some level of disturbance was anticipated from divers and this was monitored by sampling independently beforehand with a free-flushing sampler at 1 m and approximately 0.2 - 0.25 m above the bed. The absolute fluid mud concentration was of less importance here than the relative concentrations between sample sites, enabling a comparative survey of locations within the harbour exhibiting a "fluid" surface.

All samples were transferred to clean, 1 litre, labelled plastic bottles on the launch and returned to the geomorphology laboratory at the Geography Department. Volumes of samples were noted prior to filtering them through Whatman hardened, ashless filter paper (No.542) on a vacuum filtration pump. Residue was oven dried overnight at 25^{o}C, allowed to equilibrate for 30 minutes in air, then weighed. From this the original filter paper weight was subtracted. In all cases filter papers were washed, and dried overnight prior to being weighed to prevent weight loss during drying of the residue after filtration.

Twenty-one sites were sampled over a period of several months, with varying concentrations of fluid mud found at nine of them. Sampling was undertaken at various stages of both spring and neap tides under relatively calm sea conditions; the highest energy condition being a low swell. Fluid mud was found under flat calm conditions, although on these occasions the tide was running. Therefore, the presence of fluid mud under calm conditions at slack water was not ascertained. The bottom two intake nozzles were at 5.1 and 13.5 cm above the bed, and mud concentrations within the definition of fluid mud (>10 gl^{-1}) given by

Einstein and Krone (1962), and Officer (1981) were found in both bottles at two sites and in the bottom bottle only at the remaining seven sites. Figure 3.14A-I shows depth concentration curves for these samples. Thus, where it is present, fluid mud comprises a layer of approximately 10 to 15 cm thickness. Concentrations taper off rapidly above 15 cm, generally falling to a level of 100 to 200 mg l^{-1} around 30.3 cm, the fourth sample bottle. Obvious diver disturbance of bottom material was apparent in most cases where suspended sediment concentrations increased markedly in the top two bottles, at 90.4 and 99.0 cm (Fig. 3.14A,B,C & H) to levels substantially greater than the normal 60-150 mg l^{-1} at 1 m. This was probably due to suspension of material during initial positioning and settling of the instrument and caused inaccurately high concentrations in the water column. Water samples (Fig. 3.14A & B) show less disturbance below 25 cm above the bed however, and variations in near-bed concentrations in Figure 3.15 confirm the validity of utilizing this instrument to compare relative levels of bed consolidation around the harbour.

The distribution of fluid mud zones was confined to two general areas:

(1) In the channel west of Breeze Bay and extending north towards Livingston Bay.

(2) In the centre of the harbour towards the entrance and extending towards Godley Head on the northern side of the entrance.

Figure 3.15 depicts the spatial distribution of sample concentrations. Fluid mud was not located elsewhere although

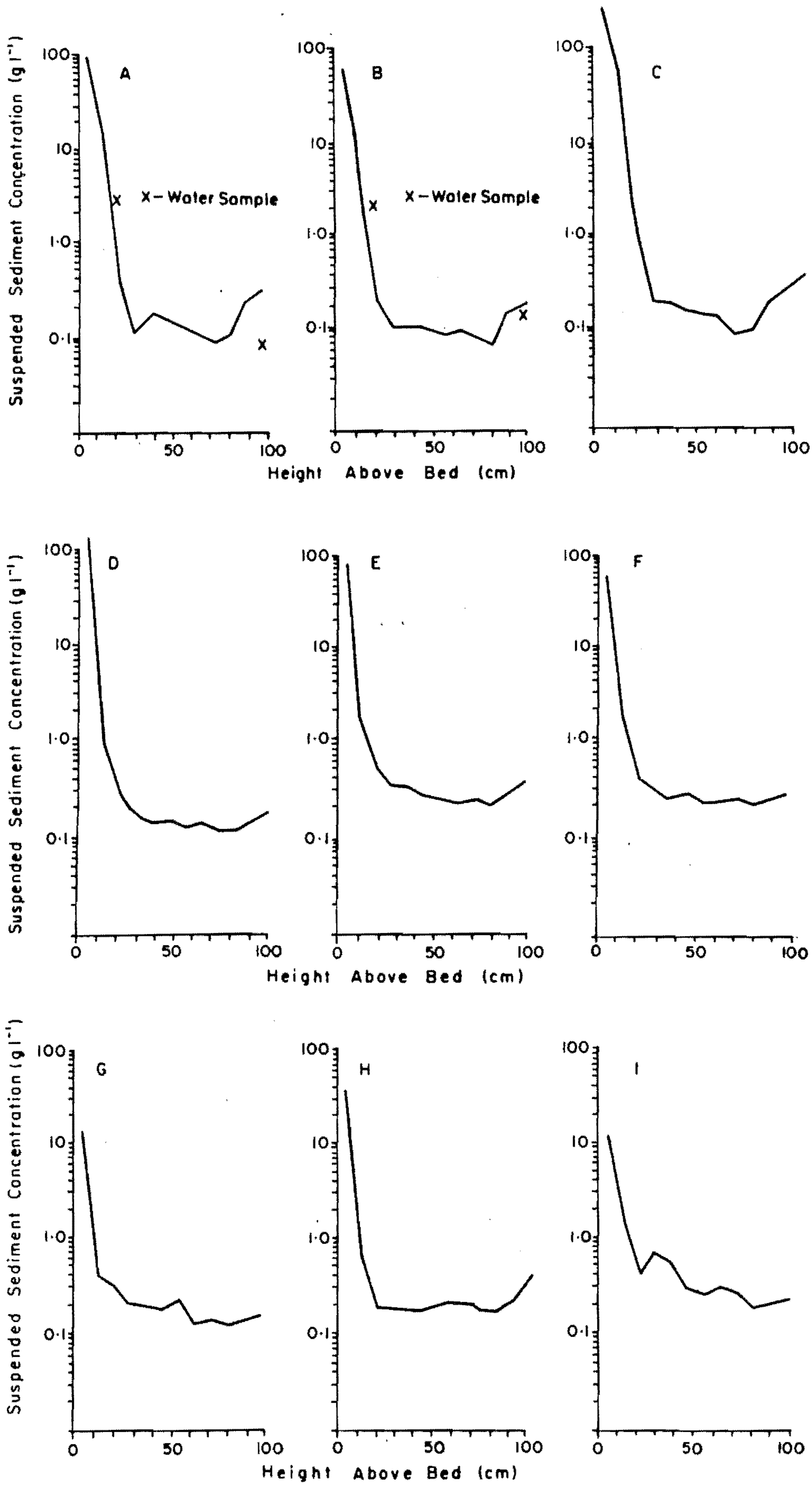


Figure 3.14 Graphs of near-bed fluid mud samples and suspended sediment profiles up to 1 m above the fluid mud layers.

near-bed suspended sediment concentrations were high between Camp Bay and Breeze Bay, and off Diamond Harbour. In the upper harbour particularly, and in sandier areas, concentrations were comparatively low. It is interesting to note that the sites with bottom concentrations of 0.6 gl^{-1} (north of Shag reef), 4 and 9 gl^{-1} (adjacent to Breeze Bay), have texturally identical bed sediments to those areas with fluid mud. Differences lie in hydraulic processes of deposition and erosion and more especially in sediment supply to each site.

Unconsolidated fine sediments of this nature are indicative of depositional zones (Håkanson, 1984) while more consolidated sediments represent areas of erosion or stability. Interpretation of Figure 3.15 suggests a down-harbour movement of clay-sized material, and lateral movement south to north from Purau Bay. Major receiving areas of these fines are in the channel, along the northern side, and in the harbour entrance predominantly on the northern side. Suspended sediment concentrations are also high opposite the breakwater near Diamond Harbour, coinciding approximately with a strong sink identified from average, whole sample relative rollability values (Fig. 3.11).

Assessment of transport and deposition mechanisms of fine clay material from this survey is more difficult. Depositional patterns are artificially complicated by the dumping of dredge spoil along the northern side east of Livingston Bay. Furthermore, the locations of the main depositional zones are atypical of estuaries and many inlets. Transport of fine sediment in well mixed and partially mixed estuaries is generally in a landward

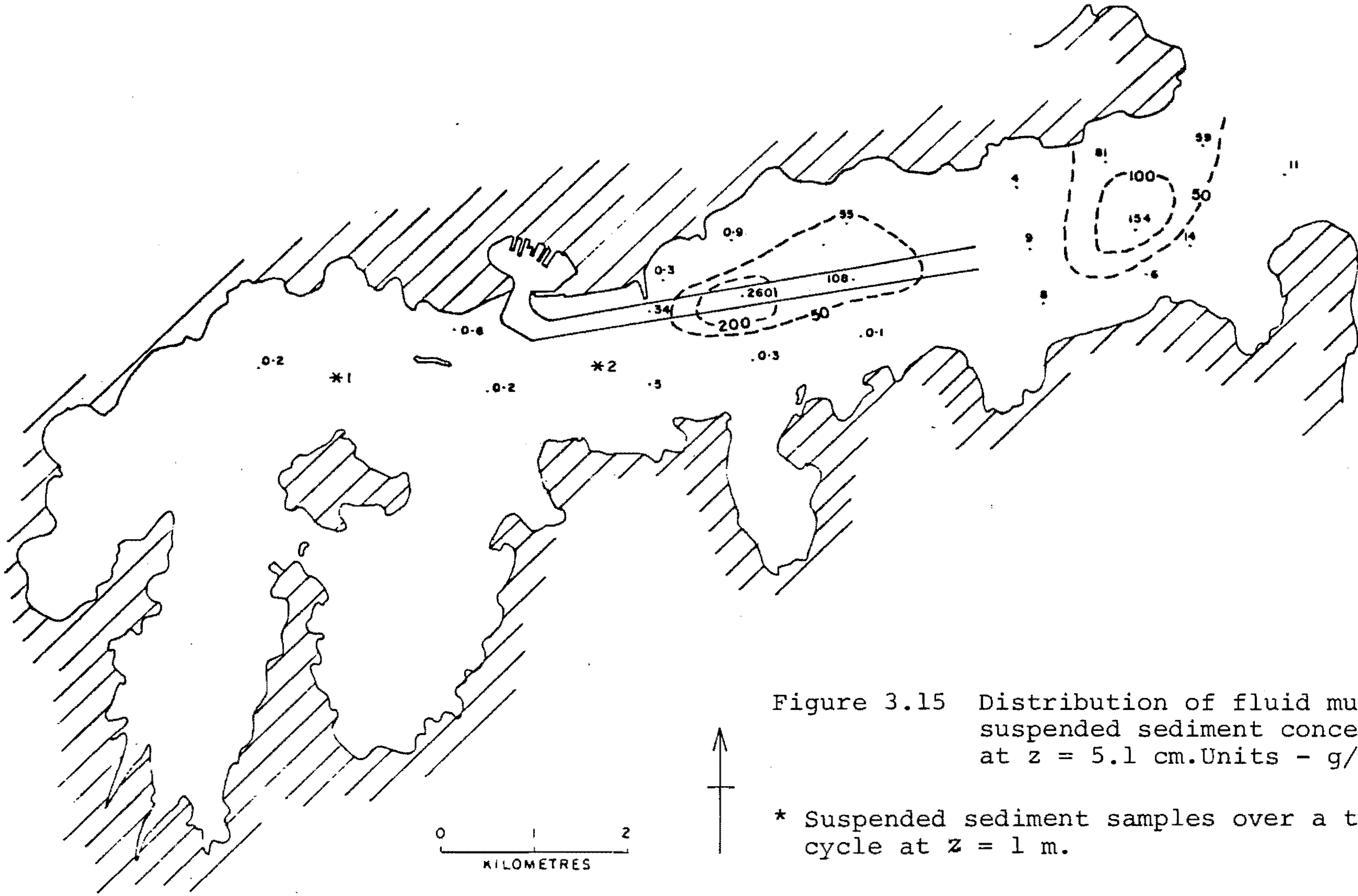


Figure 3.15 Distribution of fluid mud and suspended sediment concentrations at z = 5.1 cm. Units - g/l.

* Suspended sediment samples over a tidal cycle at z = 1 m.

direction near the bed with deposition occurring at the turbidity maximum towards the upper reaches of the estuary (Dyer, 1979; and others), while entrance deposition in tidal inlets is frequently the result of littoral drift (Bruun, 1966, 1978). Littoral drift is not present to any great extent outside Lyttelton Harbour (Herzer, 1977).

In an effort to gain insight into net transport of suspended sediments, water samples were collected at 1 m above the bed for 20 hours during two spring tidal cycles at sites shown in Figure 3.15. The results, in Figure 3.16 show a balance of suspended sediment across ebb and flood tides at site 1, and flood concentrations 12.4% greater than those on the ebb at site 2. If anything this points to a net up-harbour movement of suspended particles, comparable to the direction of sand transport proposed from rollability analysis, in which case the question of sediment origins becomes more interesting because of the depositional fluid zones in the lower harbour. Certainly dredge spoil is dumped in the lower harbour, but the occurrence of unconsolidated mud in a depositional area does not necessarily indicate transport to the area in that form (Einstein and Krone, 1962). Much suspended material moves seaward initially in estuaries (Dyer, 1979) prior to returning in a landward direction near the bed, so sources cannot readily be identified from distribution, erosion, and deposition patterns alone. Several possible sources exist for sediment input into the harbour and these will be examined below.

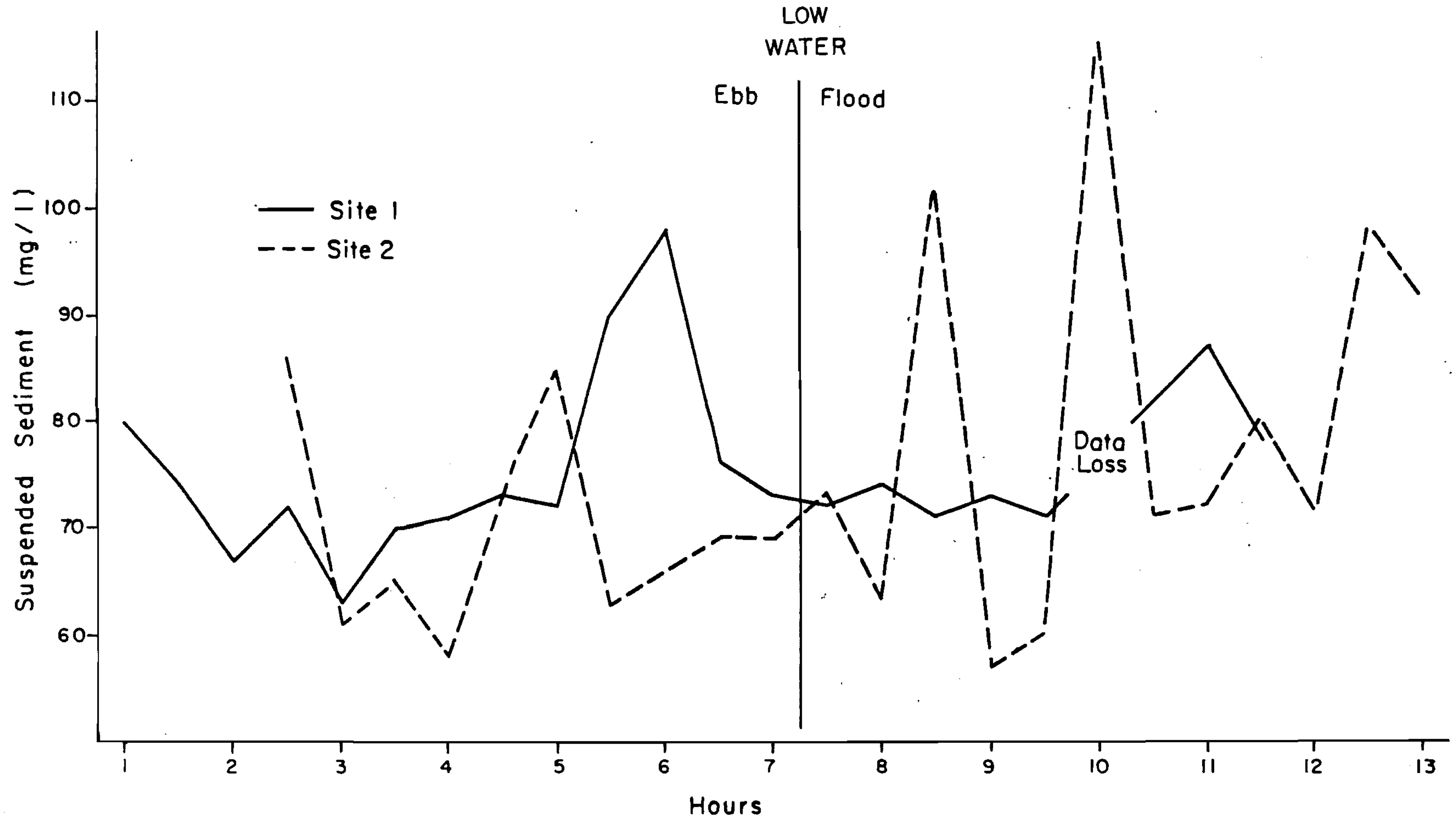


Figure 3.16 Suspended sediment concentrations at z = 1 m over a tidal cycle, at current stations 1 and 2.

3.4 SEDIMENT ORIGINS

Historically there is little question that fine sediments which now fill Lyttelton Harbour to depths of up to 47 m (Bushell and Teear, 1975) are derived largely from loess eroded from the Canterbury plains and hills. The respective percentages derived from the immediate harbour catchments and from Pegasus Bay through the harbour entrance can only be speculated on. Of more relevance to the present study, and to dredging programmes, is the immediate source of sediment entering the channel on an annual basis. Four sources are possible; erosion from the surrounding catchment; erosion of the harbour bed; sediment entering the harbour from Pegasus Bay; and recirculation of dredge spoil. Of these the former and latter were monitored.

3.4.1 Sediment Input From Catchment Erosion

Erosion is evident around Lyttelton Harbour from both aerial photographs and gullying in steep loess road cuttings, but is noticeably more apparent at the head of the harbour than along the two sides. Vertical aerial photographs taken in 1941 (Lands and Survey; run 135), 1963 (SN1408; runs 3154, 3155, 3156), and 1973 (SN2634; runs K,L,M) allowed examination of shoreline changes during those periods. Nine sites were measured (Fig. 3.17), all of which showed erosion except one (site 8; 1941-1963). Table 3.4A lists the measurements and rates of change for the nine locations. On average the shorelines in these areas, which all comprise sedimentary deposits, are eroding at 0.65 m yr^{-1} although this value is considerably enlarged by erosion rates on the exposed beach at site 7.

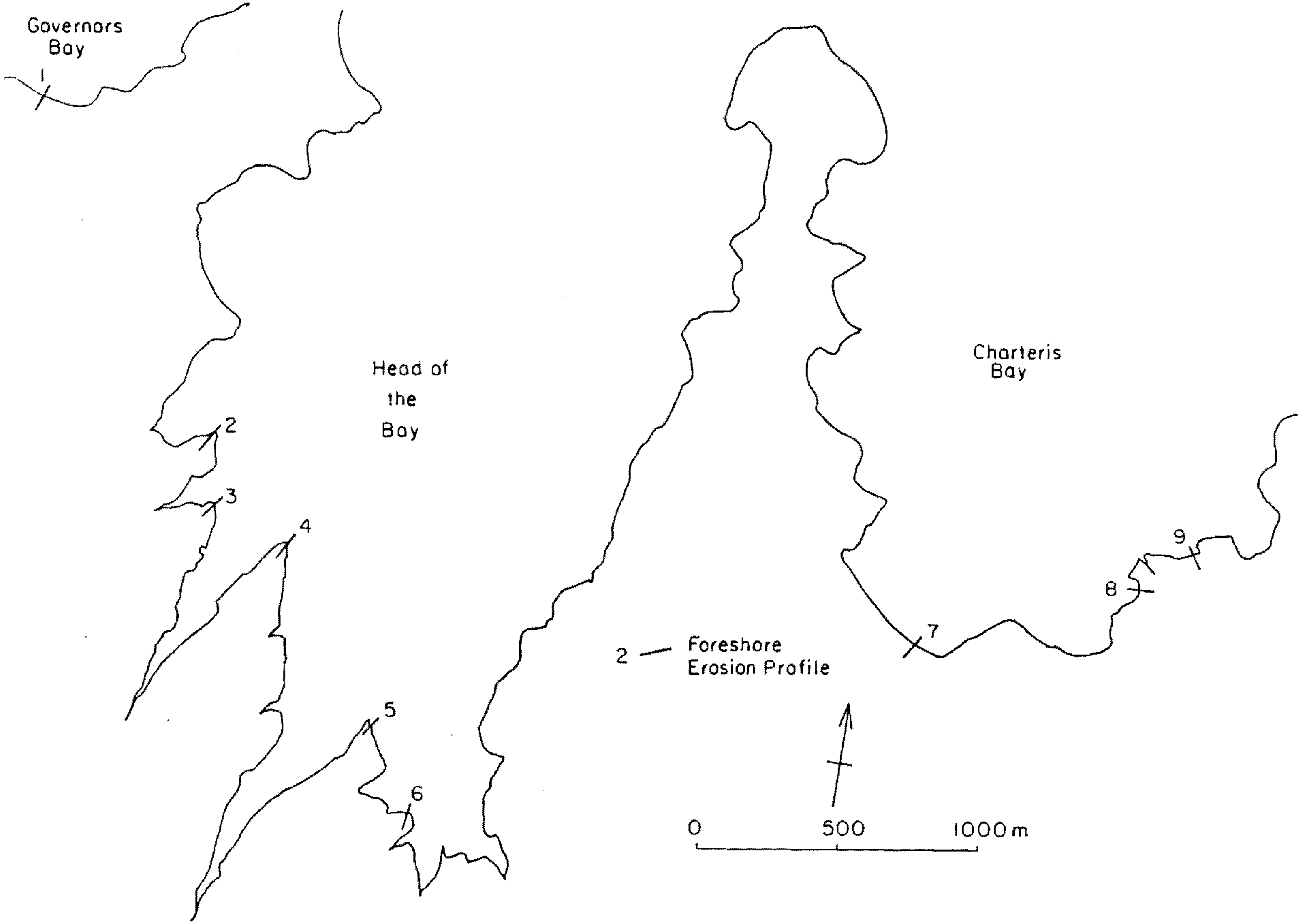


Figure 3.17 Location of foreshore erosion profile sites in Governor's Bay, Head of the Bay, and Charteris Bay.

Road cuttings were also monitored at Cass Bay, Governor's Bay, Head of the Bay, and Charteris Bay utilising spikes driven into the side of the cuttings and measured at irregular intervals. Table 3.4B lists these figures showing an average erosion rate of 0.01 $m.yr^{-1}$ This value is excessively large in terms of average erosion rates for loess deposits surrounding Lyttelton Harbour, most of which are covered in pasture or scrub and at considerably reduced gradients compared with the bare, near-vertical road cuttings. Therefore, in estimating sediment input into the harbour from loess erosion, the lowest value in Table 3.4B of 0.002 $m.yr^{-1}$ has been arbitrarily adopted as a realistic rate to apply to the total loess deposits around the harbour. This rate applied to the 19.56 km^2 of loess within the harbour catchment (Suggate, 1973), with a dry density figure for loess of 1.55 $tonnes.m^{-3}$ (Evans, 1977), gives an approximate erosion rate of 44,300 tonnes per annum, or 2.265 $tonnes.km^{-2}.yr^{-1}$. The figure is significant when compared with net change in the harbour between 1849 and 1976 (Fig.3.2; Table 3.1). The average rate of deposition during this period would have been 49,074 tonnes per annum, or 1,534 $tonnes.km^{-2}.yr^{-1}$.

It should be noted that erosion rates at the head of the harbour between Cass Bay and the Head of the Bay are substantially greater than those at Charteris Bay. Weathering of loess is measurably less along the sides of the harbour than at the head, a probable factor in the existing surface distribution of bed sediments. Between Diamond Harbour and Little Port Cooper less weathered loess presumably introduces coarser material into the harbour as

Table 3.4 Catchment erosion rates:
A. Foreshore from aerial photographs.
B. Loess road cuttings from erosion pins.

A.

Location	Site No.	Foreshore Erosion (m) 1941-1963	1963-1973	Average Rate ($m.yr^{-1}$)
Governor's Bay	1	27.6	7.8	1.11
Head of the Bay	2	5.9	4.2	0.32
	3	8.8	2.3	0.35
	4	20.3	1.2	0.67
	5	6.8	1.6	0.26
	6	3.4	1.8	0.16
Charteris Bay	7	45.3	31.0	2.38
	8	-13.4	12.6	-0.03
	9	4.9	15.8	0.65

B.

Location	Loess Road Cutting Erosion (mm) 5.11.83 to 26.2.84	26.2.84 to 4.7.84	Average Rate ($m.yr^{-1}$)
Cass Bay	9.0	8.0	0.013
	3.5	14.0	
Governor's Bay	2.0	-	0.013
	7.0	-	
Head of the Bay	3.5	15.0	0.012
	1.5	12.5	
Charteris Bay	-	0.5	0.002
	-	0.5	

it erodes while the contrary would apply to the head of the harbour. Suspended sediment loads in various streams are indicative of varying erosion rates.

3.4.2 Fluvial Suspended Sediment Load

As a further measurement of catchment sediment input, calculations of discharge and suspended load were made for a number of streams. Suspended rather than bedload was measured as channel sediments are almost totally fine clay-size material.

Four streams were sampled for suspended sediment load, and three of these were gauged for discharge following a week of moderate rainfall (Table 3.5). Stream velocities were so low however that the Head of the Bay stream was not readily measurable and streams at Governor's Bay, Charteris Bay, and Purau Bay required gauging utilizing floats, as current metering by salt dilution gauging was impractical. Measurements involved analysis of the travel times of floats over several stream cross sections in the manner outlined by Buchanan and Somers (1969) who have found that gauging of this sort can be conducted with an accuracy varying between 10 and 25%.

As can be seen from Table 3.5, fluvial input into Lyttelton Harbour is negligible supplying a minimal sediment input. Heath (1976) has calculated an average annual runoff of 1 m^3s^{-1} and an average July runoff of 5 m^3s^{-1} for Lyttelton. Using his July figure and the maximum suspended load value in Table 3.5 of 101 mg l^{-1}, an upper limit fluvial suspended sediment discharge figure of approximately 16,000 tonnes per annum is obtained. This figure is somewhat

Table 3.5 Winter stream discharge and suspended load. (July 1984).

Stream Location	Discharge (ls^{-1})	Suspended Sediment Load (mgl^{-1})
Governor's Bay	33	19
Charteris Bay	110	15
Purau Bay	195	9
Head of the Bay	-	101

reduced compared to the 44,000 tonnes derived from loess erosion, but is in the same order of magnitude. Both figures provide an interesting comparison to figures for the Pauatahanui Inlet, in a study edited by Healy (1980). This inlet is considerably smaller than Lyttelton Harbour (approximately 7 km^2) but has a mean freshwater input of 2.4 cumecs, an order of magnitude greater than that at Lyttelton. The long term mean annual suspended sediment yield based on stream data in Pauatahanui is 3,900 tonnes, although in the two year study period the total sediment mean annual yield was 13,360 tonnes. Long term, 9,600 tonnes per annum are required to sustain the estimated sedimentation rate. Based on this comparison, the lower figure for Lyttelton of 16,000 tonnes per annum would appear more likely, particularly in view of the smaller stream flow. However, even if the higher estimate of 44,000 tonnes was adopted, it is still unquestionably a minor component of the 700,000 tonnes plus annual maintenance dredging programme, for which other sources must be found.

3.4.3 Recirculation of Dredge Spoil

In chapter one the concept of achieving an optimum dredging programme was briefly outlined. In this instance, part of attaining this optimum for the Lyttelton Harbour Board entails the dumping of dredge spoil almost entirely within the harbour. Dump sites were, and are; Little Port Cooper and Camp Bay (mainly prior to 1969 and 1971 respectively); Gollans Bay (1949 to 1970); and Livingston Bay, Breeze Bay, White Patch Point, and Mechanics Bay (largely since 1969). Sites are shown in Figure 1.1.

Since 1969 dumping has been predominantly between Livingston and Mechanics Bays following a policy of forming sediment mounds along the northern side to induce wave refraction and thereby reduce wave energy. Such a reduction has been achieved (Bushell and Teear, 1975). However, dump sites have subsequently surpassed their "capacity" to hold sediment mounds, given the environmental conditions, and the bulk of spoil now dumped is removed from the site. Figure 3.18A-F demonstrates that dump sites achieve a relatively stable capacity quite rapidly, and on occasions more spoil is lost from a site than is dumped there annually.

Tonnage remaining (Fig.3.18) was calculated from depth changes between sounding charts and compared with the tonnage dumped at that site during the year. The loss rate of spoil from a given location is,therefore, merely the difference between the quantity dumped and the amount of accumulation of erosion which has occurred over a given time span (the quantity remaining). In 1982 it was calculated from these diagrams that the absolute loss of sediment from dump sites at Livingston Bay, Breeze Bay and White Patch Point was 811,000 tonnes, equivalent to 93% of the tonnage dumped at those locations, and 77% of the total quantity dumped at all sites during that year. It was also equivalent to 86% of the amount dredged in the following year, 1983. Quite clearly the dumped spoil potentially represents the major input to channel siltation on an annual basis.

Further breakdown of these data was possible by comparing loss rates between dump sites to establish from

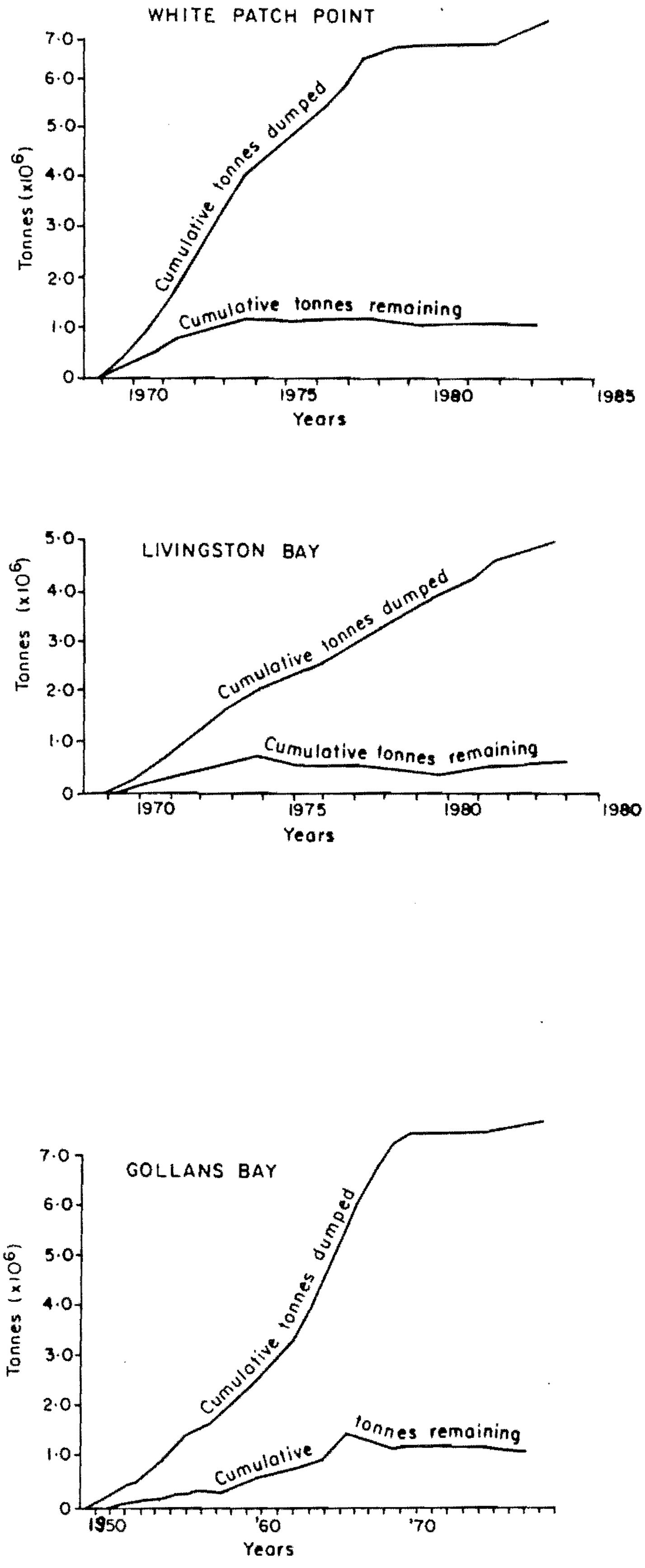
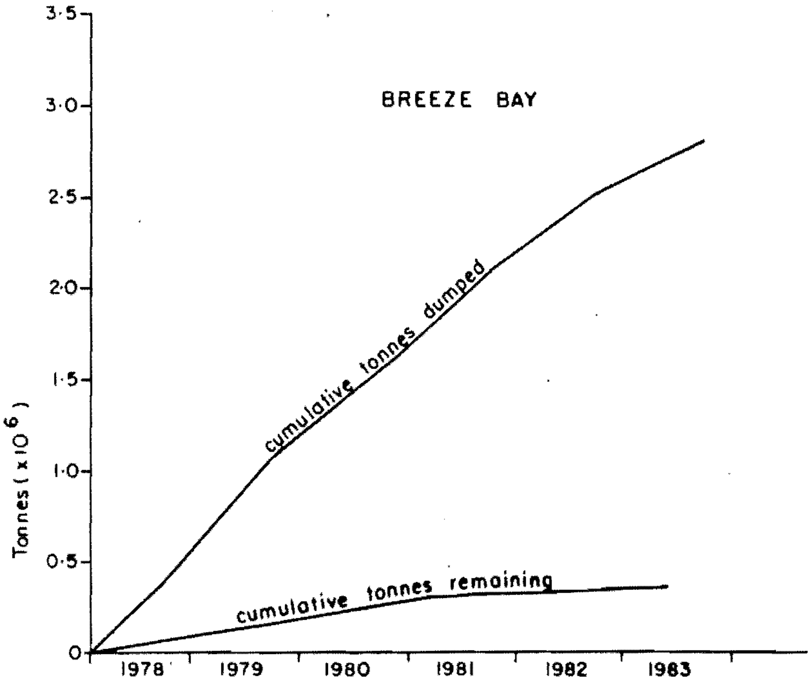
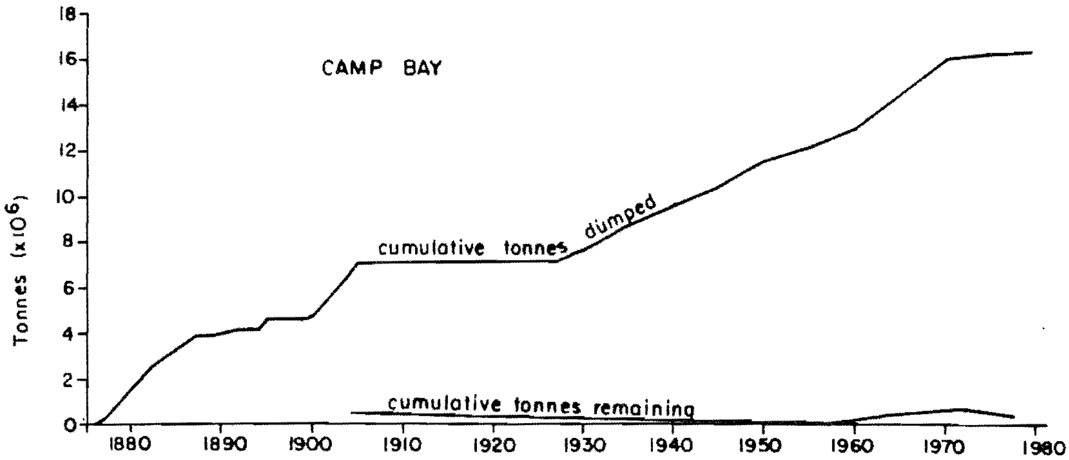


Figure 3.18 Graphs of tonnage dumped and tonnage remaining over time for harbour spoil dump sites.





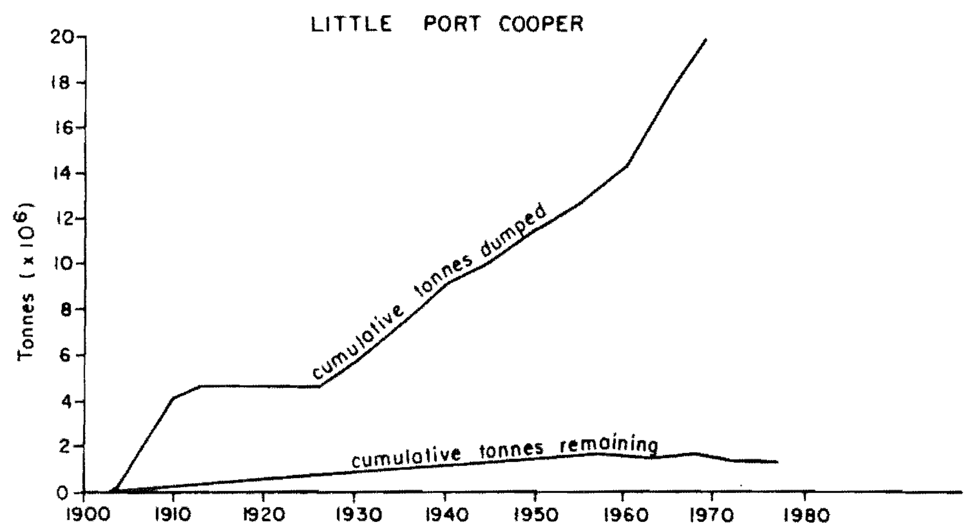


Figure 3.18 continued.

where the greatest potential source of sediment was derived. In order to achieve a comparison, areas of dump sites and the quantities dumped had to be standardised. Assuming loss rates were uniform throughout any one area surveyed, this was accomplished using the formula;

$$\frac{(L/A) \times (A/A_{max})}{D} \times 100$$

where L = tonnage lost from the site over a year

D = tonnage dumped at the site over a year

A = area of the site (m^2)

A_{max} = area of the largest site surveyed (m^2)

The resultant figure provides an area standardised value of sediment lost from each dump site in tonnes per square metre expressed as a percentage of the quantity dumped. Table 3.6 lists these values for the various locations and shows the maximum loss rate exists at Livingston Bay, followed by White Patch Point, Little Port Cooper (once site capacity is reached), and most likely Breeze Bay as well. The position of the maximum loss rate at Livingston Bay is particularly enlightening in the knowledge that dredged channel sections 131 to 145 (refer Figure 3.19), adjacent to Livingston Bay, have been identified from sounding data and dredging records as the area of maximum siltation. This region is also a depositional zone identified from the fluid mud survey (Figure 3.15). The second zone of high fluid mud concentrations lies between White Patch Point and Little Port Cooper, sites with the second highest capacity loss rates, and is a region identified as depositional from sounding charts (see Figure 3.2).

From these data there appears little doubt that spoil recirculation is the main sediment supply for depositional

Table 3.6 Tonnes.m^{-2} of sediment lost from dump sites per annum, expressed as a percentage of tonnes dumped at each site per annum.

Location	After 5 yrs Dumping	Approx. Average After Site Capacity Reached
Little Port Cooper	2.20×10^{-4}	2.31×10^{-4}
Camp Bay	-	2.22×10^{-4}
Gollans Bay	1.78×10^{-4}	2.12×10^{-4}
Livingston Bay	3.66×10^{-4}	2.44×10^{-4}
Breeze Bay	2.28×10^{-4}	-
White Patch Point	2.34×10^{-4}	2.31×10^{-4}

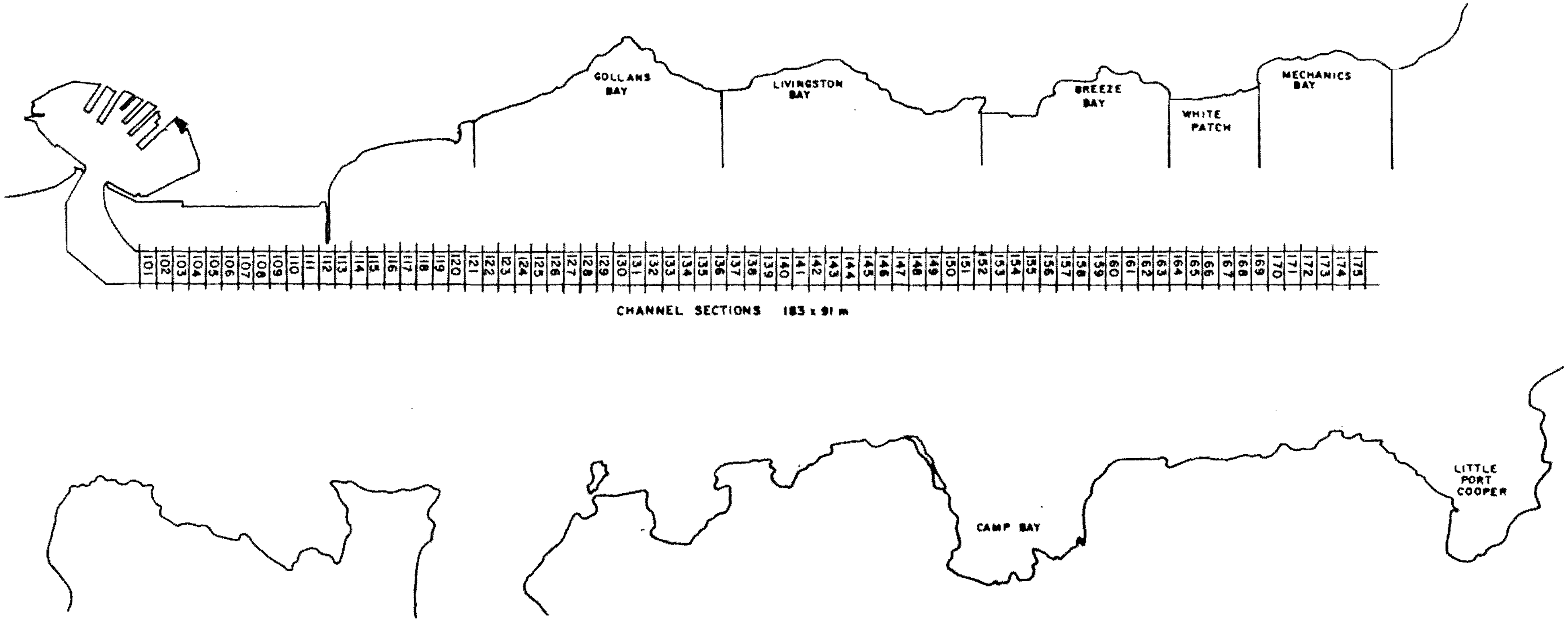


Figure 3.19 Location of channel dredge sections with respect to spoil dump sites.

zones in the outer harbour. However, mechanisms of sedimentation, and the reasons for the locations of erosional and depositional zones cannot be established solely from sediment patterns. Inferred transport directions and primary sediment sources have been identified, but distribution patterns and locations of maximum fluid mud concentrations in the entrance throat and opposite Gollans Bay (Fig. 3.15) which has the lowest spoil loss rate, can only be explained by hydraulic parameters. Certainly the combination of bidirectional transport, and the longitudinal and lateral divisions in the harbour, in terms of sediment texture and sedimentary processes, are unique in New Zealand harbours and cannot readily be explained by reference to conventional estuarine and inlet concepts.

3.5 SUMMARY

In the medium term Lyttelton Harbour is in a state of quasi-stability in terms of natural sedimentation, with a net change during the period 1849-1976 of $+3.74 \times 10^6$ m^3 deposition. The actual quantity of sediment transport and siltation occurring annually within the harbour is considerable, in the order of 4.2 to 6.0×10^5 m^3, which is a direct result of channel dredging operations. Dumped dredge spoil is recirculated into the channel and is also deposited in the harbour entrance. It represents the major sediment supply to the harbour.

Sediment distribution and mean grain size contours run parallel to the harbour longitudinal axis rather than normal to it. Thus sediment grading is across the harbour rather than along it, completely atypical of 'normal' coastal inlets, with predominantly coarser sediments on the south side and fine, clay-sized material on the north side. Some coarser material is present on the northern side east of the breakwater, but is not found in the centre of the harbour along the channel line. Fine clay sediments occur in the harbour entrance.

In general, processes can be regarded as depositonal at the head of the harbour and in the entrance, and erosional in the central region. Variations exist within this framework, with fine sand being eroded from the upper harbour north of Quail Island, and erosion in the central region occurs, predominantly on the southern side in coarser sediments. A depositional zone also exists in the central region between Diamond Harbour and the breakwater. Bidirectional transport of sand occurs on the south side, with seaward transport of sand on the north side east of the breakwater. There is no lateral movement of sand in the lower harbour east of the breakwater.

Fluid mud layers up to 15 cm deep exist in two localities; within and to the north of the channel; and in the harbour entrance. They represent depositional zones for fine, clay-sized material, maximum concentrations occurring in the channel opposite Gollans Bay and Battery Point, and in the centre of the harbour entrance opposite White Patch Point. Their presence and localities, and the lack of fluid mud in the upper harbour, support the notions of a general down-harbour movement of fine sediments and of dredge spoil recirculation.

The stability of the harbour under present environmental conditions cannot be accurately ascertained from the data presented in this chapter. Although little change has occurred between 1849 and 1976, periods of instability are apparent in the historical record and contemporary patterns show distinct regions of depositional and erosional processes occurring within the harbour. These data answer one of the major scientific questions posed about the harbour stability in chapter one. The harbour was, "historically", not in a state of equilibrium, with sedimentary processes fluctuating both spatially and temporally between erosional and depositional. However, answers to other questions posed, regarding the response of the harbour to dredging, and the controlling factors of both historical and contemporary stability conditions cannot be obtained from these data alone. Additional data are required to assess the present stability state. Further to this, additional data are required to assess the precise transport mechanisms and directions of fine grained sediments. The mud and grain size distribution patterns are atypical of other inlets described in the literature, and cannot be explained by generally applied concepts pertaining to estuarine and inlet hydrodynamics.

FOUR

HYDROGRAPHY

A basic characteristic of the hydrography of any inlet system is the circulation structure, which is established and driven by mechanisms operating within the inlet. Frequently a number of driving forces exist, which may include;

(a) Forcing functions (e.g. tides and weather related phenomena).

(b) Boundary interactions (e.g. local eddies caused by breakwaters or headlands).

(c) Gravitational or density functions (e.g. estuarine circulation induced by density differences between fresh and salt water).

Temporal and spatial variations in sedimentation will reflect the type of circulation operating in a given inlet in the manner outlined briefly in chapters one and two where turbidity maxima and tidal asymmetry were discussed. The combination of internal circulation and sedimentation patterns, and entrance or external influencing factors such as longshore currents and littoral drift, provide the controlling mechanisms for inlet stability. Thus it is primarily the hydrography of an inlet and the influence it has on sedimentation which differentiates one inlet from another.

However, while circulation patterns in estuaries are well documented, there has been little emphasis placed on circulation in non-estuarine tidal inlets with the exception of various case studies (e.g. Brodie, 1955, 1958; Davis-Colley and Healy, 1978a; Heath, 1977; Heath et al. 1977, 1983; Millar, 1980). Fewer studies have undertaken detailed analyses of circulation and sedimentation in tidal inlets. A number of studies have examined tidal circulation and eddies effected by topography and boundary geometries (Ferentinos and Collins, 1979; Sugimoto, 1975). Eddies and circulation of this nature do occur in Lyttelton Harbour.

Therefore, the purpose of this chapter is to examine the hydrography of Lyttelton and determine the degree of influence that the three types of driving forces previously mentioned, (forcing functions, boundary interactions, and gravitational and density functions), exert on the harbour system. The influence on sedimentation of the circulation will be examined briefly, and then discussed in more detail in chapters five and six. Finally, the notion of classifying Lyttelton based on the hydrography of the harbour will be examined briefly in this chapter, and in detail in chapter seven.

4.1 SALINITY AND DENSITY CURRENTS

In classifications and definitions of estuaries by Cameron and Pritchard (1963), Hansen and Rattray (1966), and others, the definitive parameter is the saline/fresh water ratio, and in particular the extent to which vertical and horizontal salinity gradients are present. With this in mind, some assessment of salinity gradients is essential not only to establish the main mechanisms driving currents and circulation, but also to achieve an understanding of the fundamental concepts behind the harbour dynamics; how they operate, and how they should be approached in a scientific context.

Two surveys were conducted. The first was a longitudinal profile taken around low water during May 1984 when fluvial input was relatively low. The second concentrated around the head of the harbour where combined fresh water inputs are maximised, and was taken on 1 October 1984 immediately following an intensive 24 hour period of heavy rain. Discharge of streams around the harbour is generally low and although no measurements were obtained during the survey periods, Table 3.5 provides figures for moderate discharges in several of the larger streams.

Figures 4.1, 4.2 and 4.3 illustrate the profiles and surface spatial patterns from the two surveys. From Figures 4.1 and 4.2A it can be seen that three divisions exist along the longitudinal harbour axis, with salinity values of $33^{o}/oo$ or greater being recorded in two regions; at sites 6 and 7 adjacent to the port in the centre of the harbour, and at sites 12, 13 and 14 towards the entrance. The water column was well mixed inside the entrance as far as site 10, and at site 4 between Quail Island and Cass Bay. Between these two sites mixing was less complete and vertical profiles between sites 4 and 6 approached those commonly associated with partially mixed estuaries (Pritchard, 1967a; Fig.2). Landward of site 4 mixing was less complete again and the vertical profile displayed a degree of stratification. It should be noted that maximum vertical variation in salinity was $0.5^{o}/oo$ at site 6, and generally variation was less than $0.2^{o}/oo$

As was found in chapter three with respect to

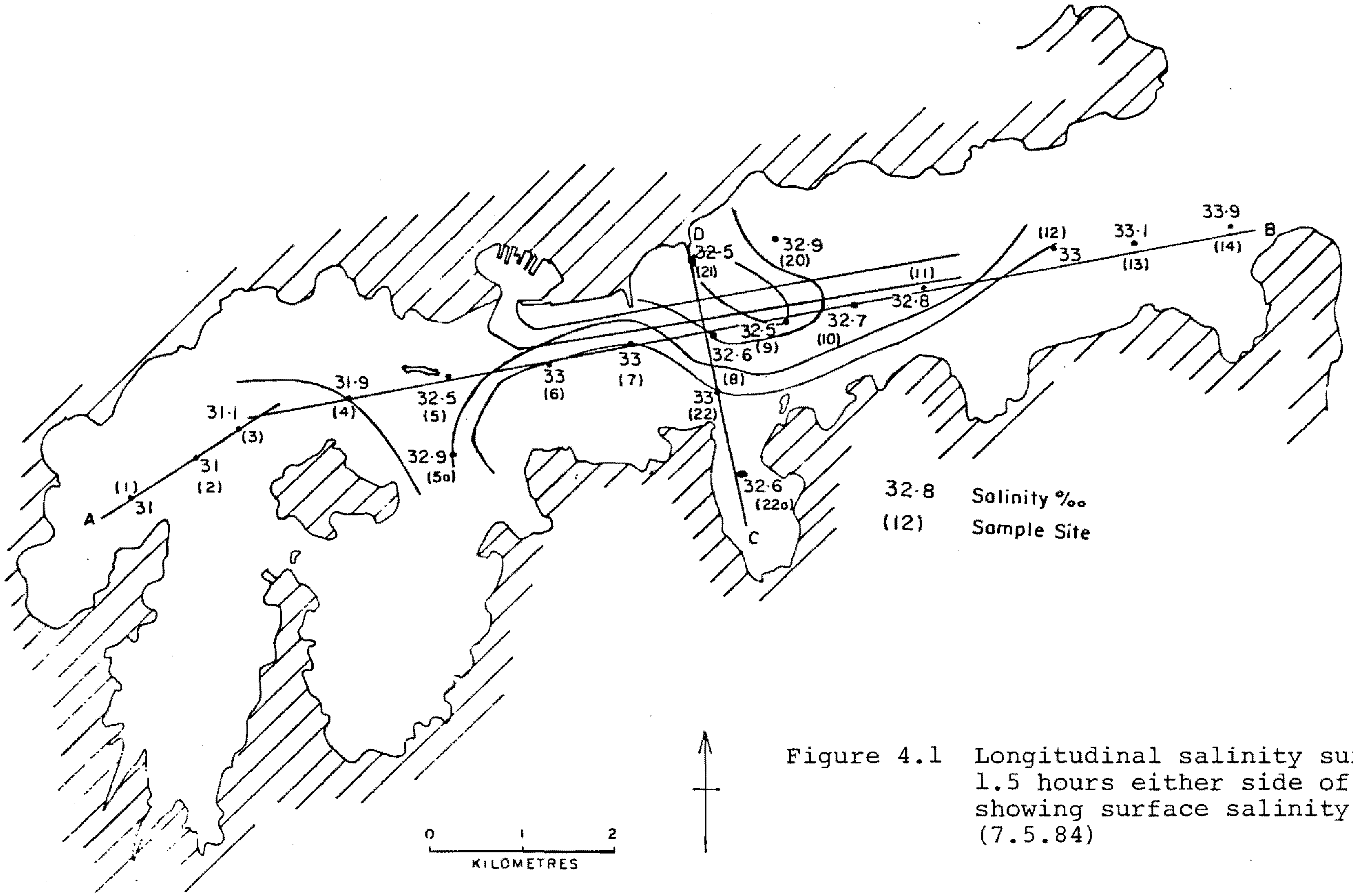


Figure 4.1 Longitudinal salinity survey 1.5 hours either side of low water, showing surface salinity values. (7.5.84)

sedimentary patterns, the longitudinal salinity profile distinguishes, longitudinally, between upper and lower harbour regions of dynamics. The two are separated by the narrow centre of the harbour which appears to act as a seaward limit to the upper harbour system, reaching salinity values of $33^{o}/oo$. Values then fell to a low of $32.4^{o}/oo$ seaward of site 7 where the harbour widens again and the lower harbour 'system' is entered. Such a reduction in salinity was not associated with the fresh water input from the Purau Bay stream as indicated by the high salinity contours across the entrance to Purau Bay (see Figure 4.1). Thus the separation of the harbour into two salinity regions, deviating primarily in salinity values rather than in degree of mixing (the norm for harbours with several salinity structures; e.g. the Hudson River), must be a function and reflection of the overall harbour hydrodynamics. The region around sites 6 and 7 could be regarded as a transition zone between upper and lower harbours (respectively west and east of the area between the port and the breakwater), illustrated this time in terms of mixing variations.

A simultaneous temperature survey along the same profile, and shown in Figure 4.2B, does not mirror the salinity patterns, but shows similar well mixed characteristics. Water density is a function of temperature as well as salinity, although to a far lesser degree since the temperature range in an inlet is usually small (Dyer, 1973). However, there is evidence for a warm underflow at the head of the harbour which may be associated with warm water from shallow catchment streams. This is significant for sedimentation, since fluvial suspended load would be introduced at the bottom of the sea

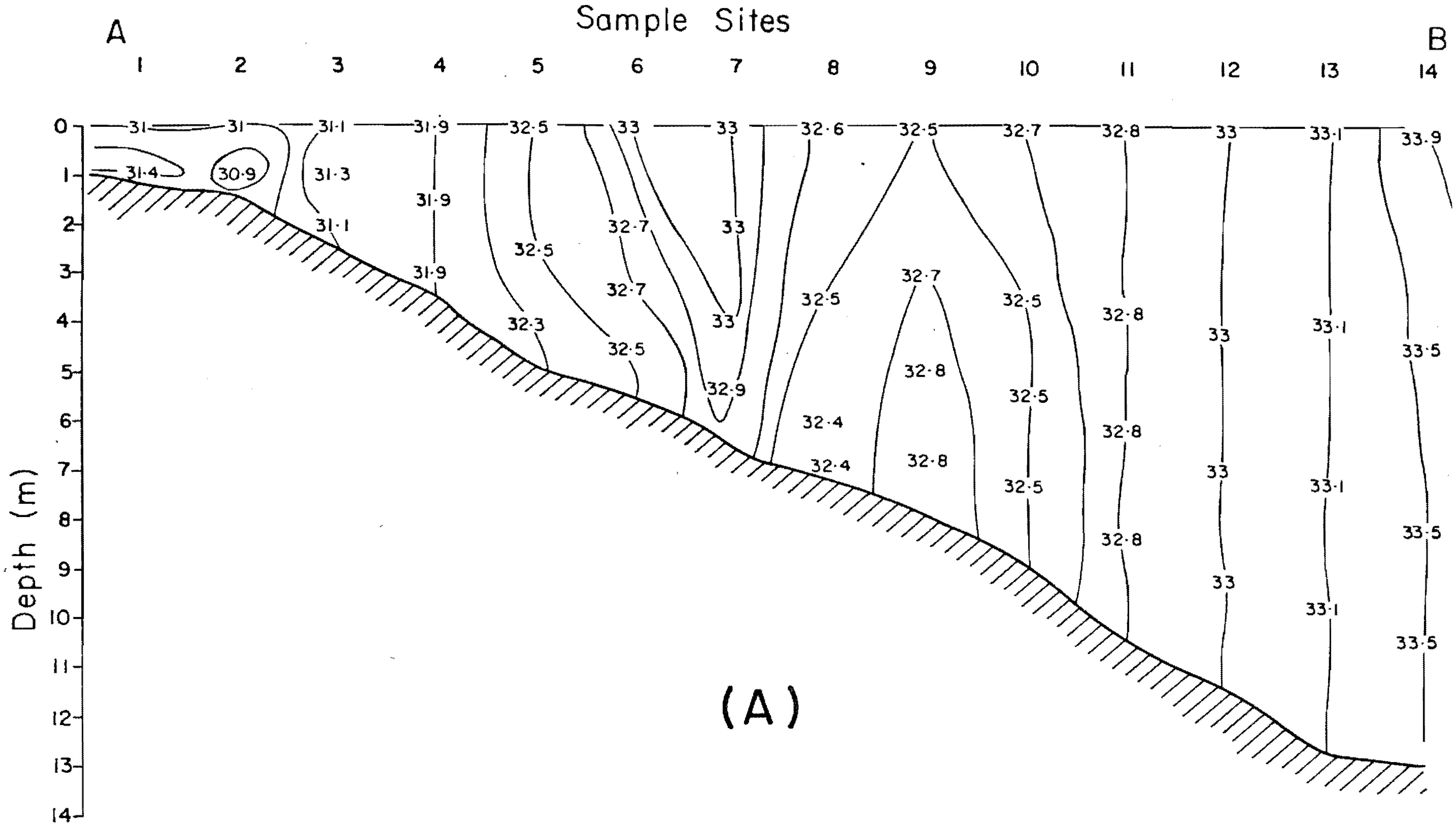


Figure 4.2A Longitudinal salinity survey showing the vertical profiles. (7.5.84)

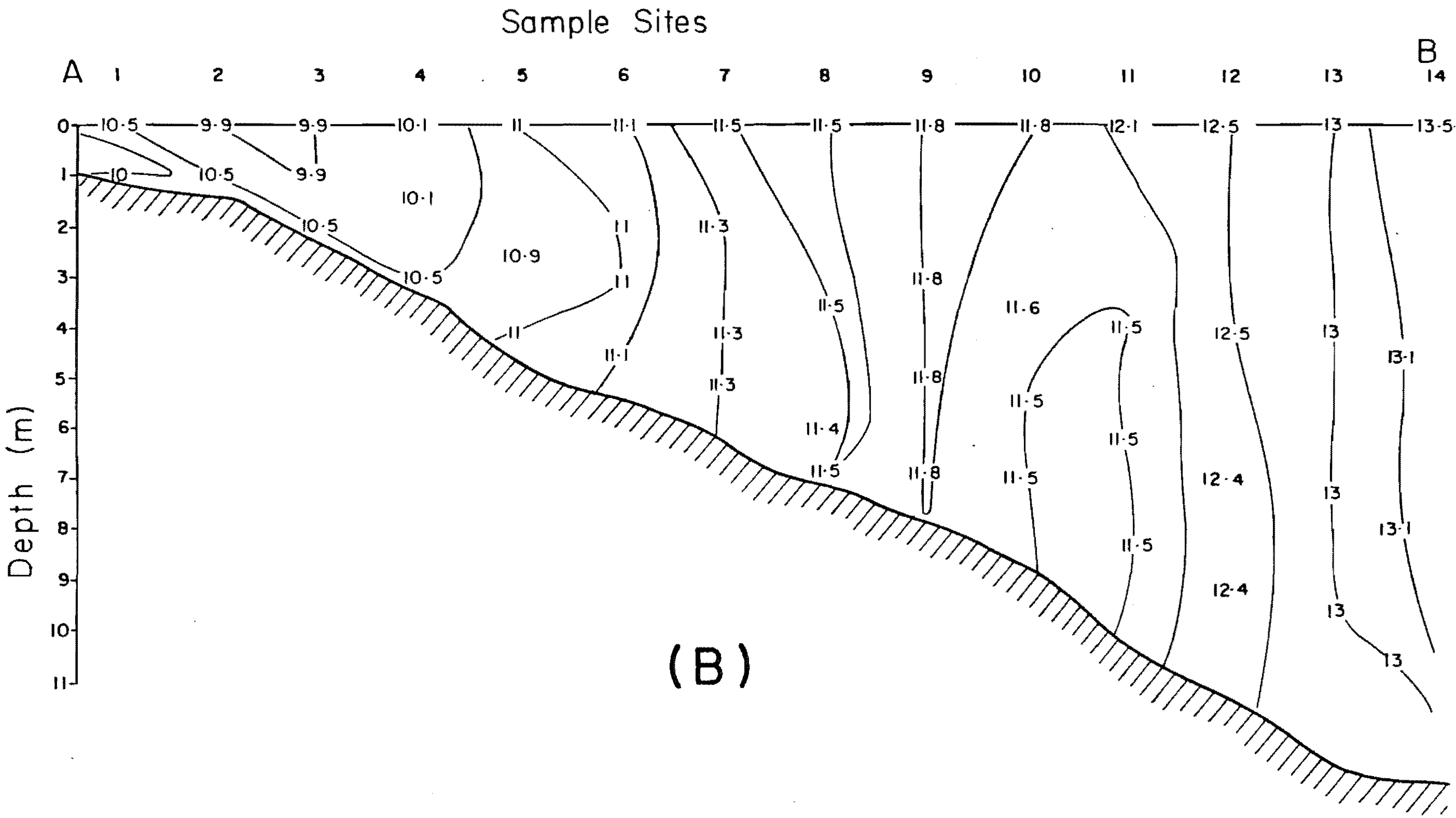


Figure 4.2B Longitudinal temperature survey showing vertical profiles. (7.5.84)

water column and would therefore be deposited more rapidly, having less vertical distance to settle. This would contribute to deposition at the head of the harbour, as indicated by historical bathymetric data (Fig. 3.2), rather than to deposition further along the harbour towards the entrance.

Attention must now be drawn to the longitudinal gradient in salinity, overall a mere $3\,^{o}/oo$ increasing seaward with the exception of sites 8, 9 and 10. More importantly, the minimum salinity recorded was $30.9\,^{o}/oo$ which raises questions pertaining to the somewhat arbitrary term in Cameron and Pritchard's (1963) estuarine definition (see section 2.1), "measurably diluted", which refers to the dilution of salt water in an inlet by fresh water derived from land drainage. Certainly a salinity gradient was measurable in Lyttelton Harbour. However the minimum value was not far in excess of dilute salinities found in patches of ocean water. In effect, identifiable bodies of fresh water, and therefore density gradients, were absent during the survey.

To assess this 'estuarine' concept further, a second survey was conducted when fluvial discharge was near maximum immediately following a southerly storm which brought high intensity precipitation. The results (Fig. 4.3B) were similar to the first survey. Salinities were high and all sites exhibited vertical homogeneity except site 1, which had a surface value of $31.5\,^{o}/oo$ and a bottom value of $32\,^{o}/oo$ in 1.5 m of water, indicative of slight stratification towards the fresh water input. Again fresh water was absent in the survey and there was no indication that density gradients, either horizontal or vertical, were of sufficient magnitude to induce currents and circulation of any significance.

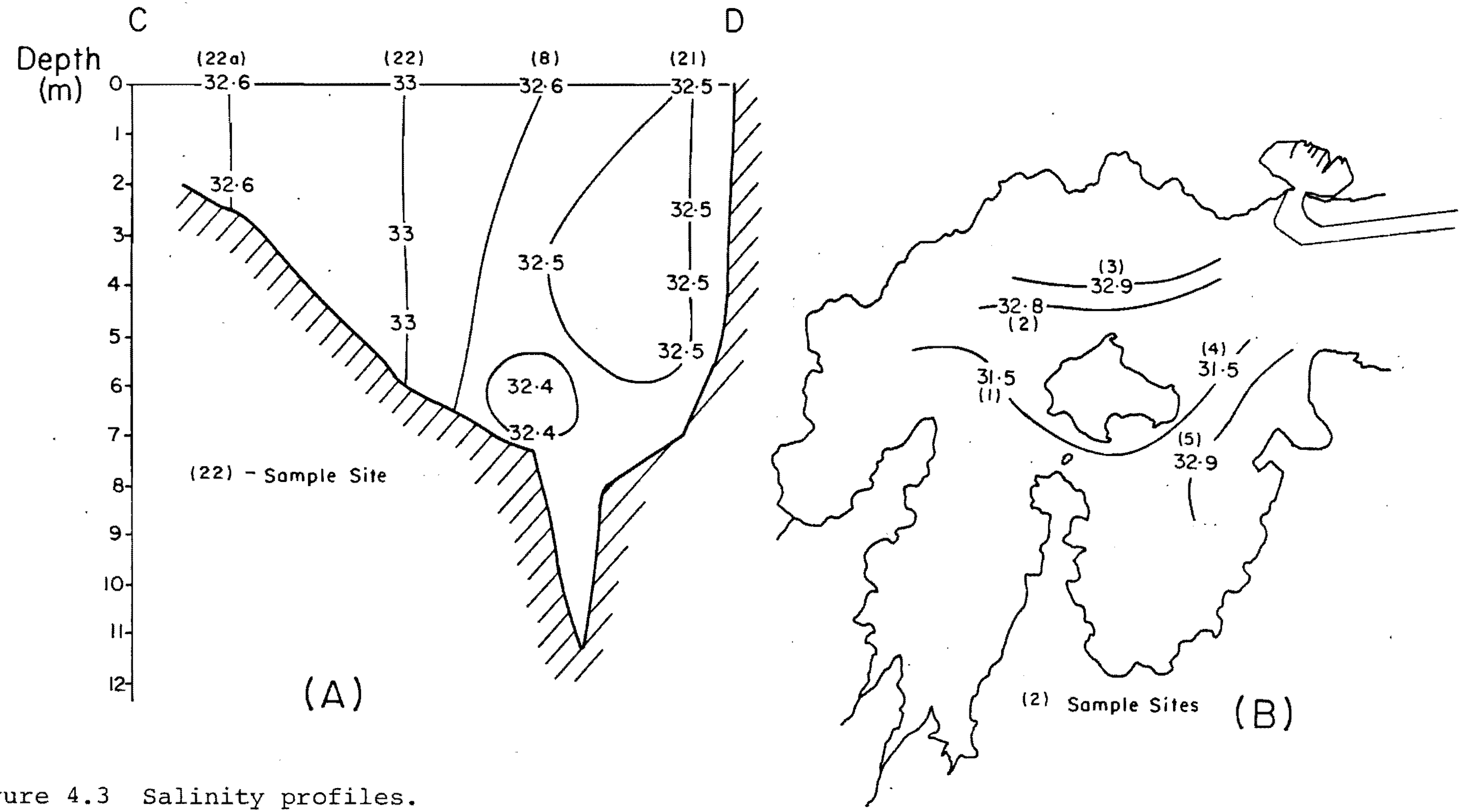


Figure 4.3 Salinity profiles.
A. Cross-sectional harbour profile (7.5.84). Location $\overline{CD}$ shown in figure 4.1.
B. Surface values in the upper harbour following heavy rain (1.10.84).

4.1.1 Circulation and Density Currents

Classic circulation patterns in estuaries show a vertical water rotation with landward flow near the bed and seaward flow on the surface (Bowden, 1967; Pritchard, 1955), or landward flow near the bed and surface, with seaward flow in the centre of the water column (Pritchard, 1971; Fig.19). Such circulation results from density differences between fresh and salt water, and the maintenance of longitudinal salt continuity within the estuary (discussed in chapter two). However in these cases there is invariably a large salinity range encountered in the estuary, from fresh water to values approaching that of seawater. It has already been shown that this is not the case in Lyttelton.

Obviously, a further important parameter inducing density currents is the vertical salinity range at any given site. Bowden (1960) measured vertical salinity differences of $1^{o}/oo$ in the "Narrows" of the Mersey estuary, (previously regarded as essentially vertically homogeneous), and found a significant, net non-tidal circulation similar to the James River with $3^{o}/oo$ vertical variation (Pritchard, 1967a). Recorded variation in the vertical in Lyttelton Harbour is generally less than $0.5^{o}/oo$, as already stated. However, Bowden (1967) postulates that differences as low as $0.1^{o}/oo$ might enable a significant transport of salt to be produced. Irrespective of this, it can be demonstrated that 'estuarine circulation' is unlikely to develop in Lyttelton if salt transport is occurring under the conditions surveyed. Consideration again of Figure 4.2A will show that with the exception of sites 8 and 9 and well mixed regions, salinity contours slope towards the sea, quite the opposite to contours in stratified and partially mixed estuaries. Thus the inferred circulation is landward on the surface and seaward near the bed, totally atypical of accepted, density-driven circulation patterns in inlets.

Evidence of lateral circulation is illustrated by Figures 4.1 and 4.3A which both indicate reduced salinities on the northern side of the harbour, specifically east of the breakwater. This results from movement of water across to the north side of the harbour and is more probably caused by Coriolis forces rather than by density currents. Such a lateral salinity gradient is common in many inlets and estuaries but is not a reflection of estuarine conditions.

Effectively then, Lyttelton Harbour can be termed non-estuarine, and any density currents which do occur will be in close proximity to the stream mouths. This is due principally to the high salinities and small longitudinal gradient in the harbour preventing the development of density currents and circulation patterns of appreciable scale. Thus, without the formation of estuarine phenomena such as turbidity maxima or layered, bidirectional flow, sediment distribution throughout the harbour will be controlled by tidal and/or meteorologically induced currents. From the above evidence it seems likely that these 'forcing functions' will provide the main driving mechanisms for the harbour circulation and hydrography.

4.2 TIDAL PHENOMENA

The active presence of tidally generated forces at coastal inlets with an opening to the sea is accepted as a normal occurrence, but the degree to which tidal forces influence an inlet, and the manner in which they are influential, varies widely and requires careful appraisal at any site.

The significant tide generating forces are produced by the relative configuration and mutual gravitational forces between the Earth, Moon, and Sun. From Newton's law of gravitation it is apparent that the greatest influence on tides is exerted by the Moon, which produces the major semi-diurnal and fortnightly (spring-neap) components so apparent to a casual observer. One revolution of the Moon with respect to the earth takes 24 hours and 50 minutes, so that successive high or low tides are 12 hours and 25 minutes apart on average; ebb and flood tides taking 6.25 hours.

In an estuary the tidal wave form becomes distorted as it travels inland owing to reduced wave speed as depth decreases, ensuing friction and freshwater flow. The distance travelled by the crest in a given time exceeds that travelled by the trough, and consequently the wave form becomes more distorted the further inland it travels in shallow water (McDowell and O'Connor, 1977). The result is that the time taken for the tide to flood within an estuary decreases at points further inland and, since the process repeats itself every 12.42 hours, the ebb flow is correspondingly longer. Defant (1961; p.458) lists data for 22 sites on six major world estuaries demonstrating such tidal wave asymmetry.

At Lyttelton a tide gauge is situated in the inner harbour, 9 km from the entrance, where depths are approximately 12.9 m (MSL) as a result of berthage dredging. The natural change in depth from the harbour entrance to directly opposite the gauge outside the port moles is 9.3 m. Spring and neap tide range at this site are 1.92 m and 1.67 m respectively.

Examination of the record from 3 September to 31 October 1984, depicted in Figure 4.4, shows a somewhat irregular pattern of asymmetry. Maximum and minimum durations of flood and ebb tides were 8.25 and 5.0 hours, and 8.0 and 5.0 hours respectively for this record period. At times the flood is longer than the corresponding ebb and vice versa, and on other occasions the two are balanced. On average, the duration of the flood is 6.29 hrs, six minutes longer than the average ebb of 6.19 hrs, which combine to give approximately 12 hrs, 25 mins. per tidal cycle. Figure 4.5 shows the tidal variability for the period, expressed as residuals for ebb and flood tides; the observed duration minus the expected duration. Thus the two plots show variations in the tide caused by factors other than the normal tidal constituents used in predictive models. Clearly there is considerable variation in the length of the tides. Both flood and ebb vary in a comparable manner, although flood tides appear to be relatively longer (greater positive residuals) more frequently. Equally there is no systematic pattern to these variations, causes of which will be discussed in the following section.

A further inequality in the tide should also be noted. This is a diurnal inequality resulting from an increase in the strength of lunar constituents when the moon is in its upper transit, or more directly overhead, and causes the amplitude of the 'night-time' tides to be as much as 0.25 m greater than that of the 'day-time' tides (apparent in Figure 4.4).

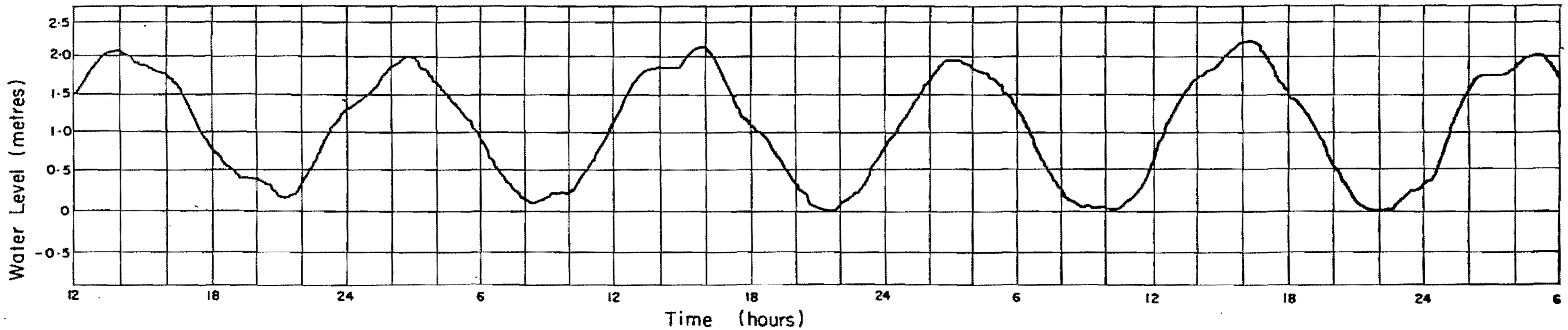
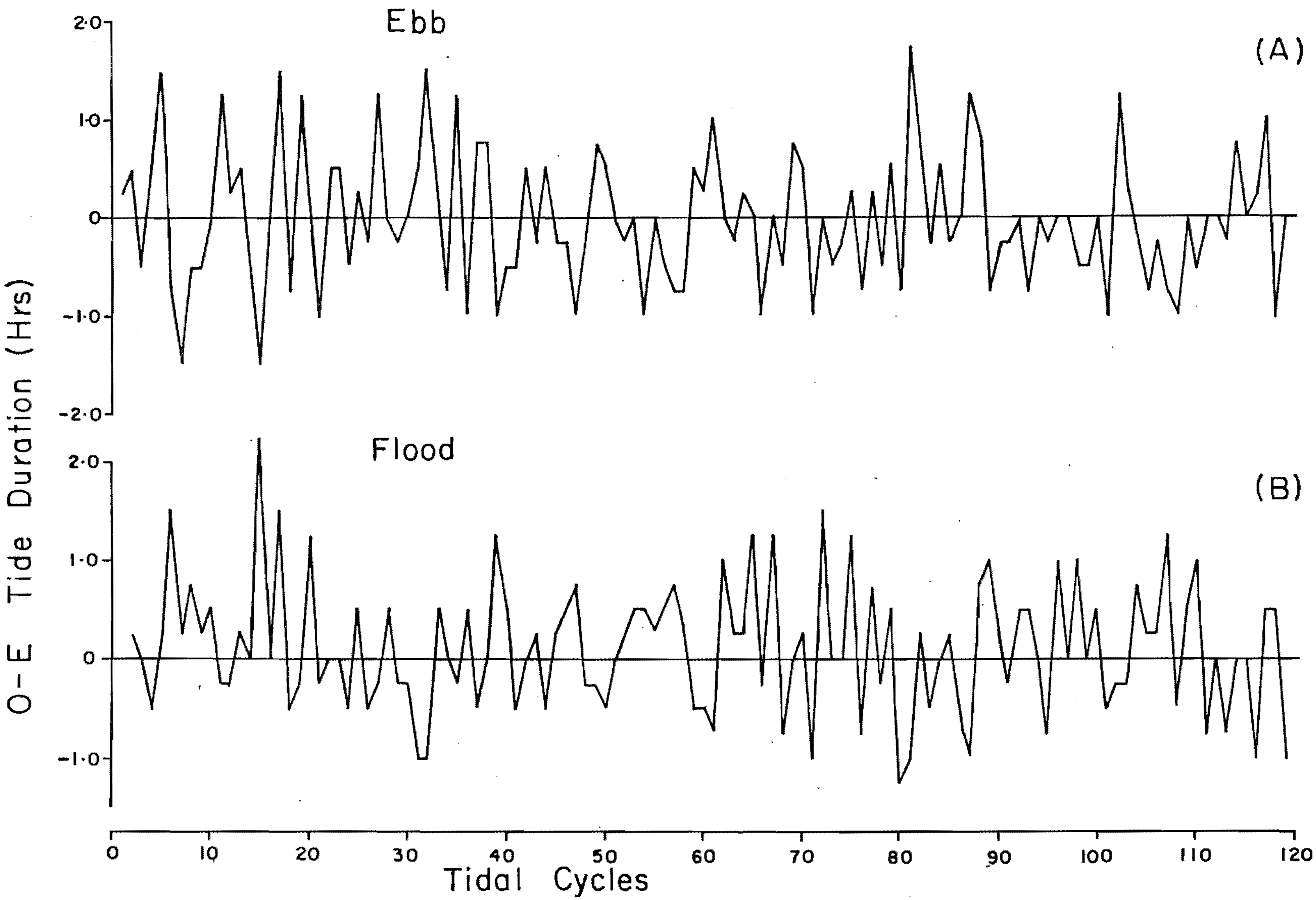


Figure 4.4 Extract from the tide gauge water level curve from 24.8.84 to 27.8.84. Protuberances are associated with edge wave oscillations.

Figure 4.5 Graphs of tidal residuals for ebb and flood tides: Observed tidal duration minus expected duration from tide charts.


Ebb
(A)
Flood
(B)
O-E Tide Duration (Hrs)
2·0
1·0
0
-1·0
-2·0
Tidal Cycles
0
10
20
30
40
50
60
70
80
90
100
110
120

4.2.1 Spectral Analysis of the Tidal Wave

Spectral analysis of the tidal wave was carried out to establish the main components generating or forcing the tide at Lyttelton, and to examine causes of variability in flood and ebb duration. While the numerous tidal constituents are always present, many are negligible and the influence of each, particularly the lesser ones, will vary from place to place. Influences from external factors such as surges and meteorological effects may also be present to varying degrees. Lisitzin (1974; p.12) lists some important tidal constituents and their relative coefficients, some of which are reproduced in Table 4.1.

The spectral analysis programme utilised here is based on the Fast Fourier Transform and is explained in detail by Thrall and Engleman (1981). Essentially the programme fits a series of sine waves to the tidal data using the Fourier transform and calculates periodograms for the data series. A periodogram is the square of the rescaled amplitude of the series after fitting a sine wave, and may be regarded as a crude estimate of the spectral density (Thrall and Engleman, 1981). In calculating a spectral density for the time series the data are represented as a sum of sine waves at a discrete set of equispaced frequencies which range from zero to the highest frequency discernible in the data set, determined by the data sampling interval. At each frequency the amplitude and phase of the best fitting sine wave are determined, from which periodograms are calculated. The spectral density estimate at a frequency is then formed from a weighted average of adjacent periodograms.

The nature of the programme output, and the fact that

Table 4.1 Some tidal constituents and their characteristics

Symbol	Angular Speed (Degrees hr^{-1})	Relative Coefficient	Definition of Symbols
M_N	0.0022	0.0655	Constituents covering several years (e.g. 19 year lunar nodal cycle)
S_a	0.041	0.0188	Solar annual
S_{sa}	0.0821	0.0729	Semi-annual
M_m	0.5444	0.0825	Lunar monthly
M_f	1.0980	0.1564	Lunar fortnightly (spring and neap)
Q_1	13.3987	0.0722	Variations in distance between Moon and Earth
O_1	13.9430	0.3769	Dependent on lunar declination
P_1	14.9589	0.1785	Dependent on solar declination
K_1	15.0411	0.5305	Associated with both declinations
J_1	15.5845	0.0296	Variations in distance between Moon and Earth
N_2	28.4397	0.1739	Due to ellipticity of Moon's orbit
M_2	28.9841	0.9081	Principal lunar tide
L_2	29.5285	0.0257	Due to ellipticity of Moon's orbit
T_2	29.9589	0.0248	Due to ellipticity of the solar orbit
S_2	30.0000	0.4236	Principal solar component
K_2	30.0821	0.1151	Variations in both declinations

the sampling interval determines the frequency range, meant it was difficult to create a spectrum covering both the long and short period tidal components simultaneously. It was therefore decided to run two spectral analyses, one at the long period end of the spectrum and one at the short period end, with several components common to both. For the long period analysis, a year of tidal data were used, from 12-2-81 to 12-2-82, at a sampling interval of 4 hrs, while the short period spectrum was created from eight days of data (20-8-84 to 27-8-84) at a sampling interval of 15 mins. In both instances data comprised tidal elevations taken from the tide gauge record. Figures 4.6A and B show the long and short period spectra respectively, and Table 4.2 lists the main power density components and their origins.

Examination of Figure 4.6A reveals the relative magnitude of the M_2 principal lunar constituent, which is the main component of the Lyttelton tides. Its relative power in the density spectrum (Table 4.2A) is two orders of magnitude greater than the next most important component S_2, the principal solar tide. M_2 and S_2 generate the semi-diurnal tides causing two highs and two lows per day.

Following M_2, the power densities of S_2, K_1 and M_f are all of approximately equal magnitudes. What is significant is the weather forcing component which is of the same order of magnitude as S_2 and greater than K_1. The implication is that weather cycles are as influential to water levels and currents at Lyttelton as the K_1 and M_f components which generate readily measurable and observable effects. The period of the weather component is 11.4 days which corresponds well to a significant 10.75 day peak in the spectrum of four hourly pressure

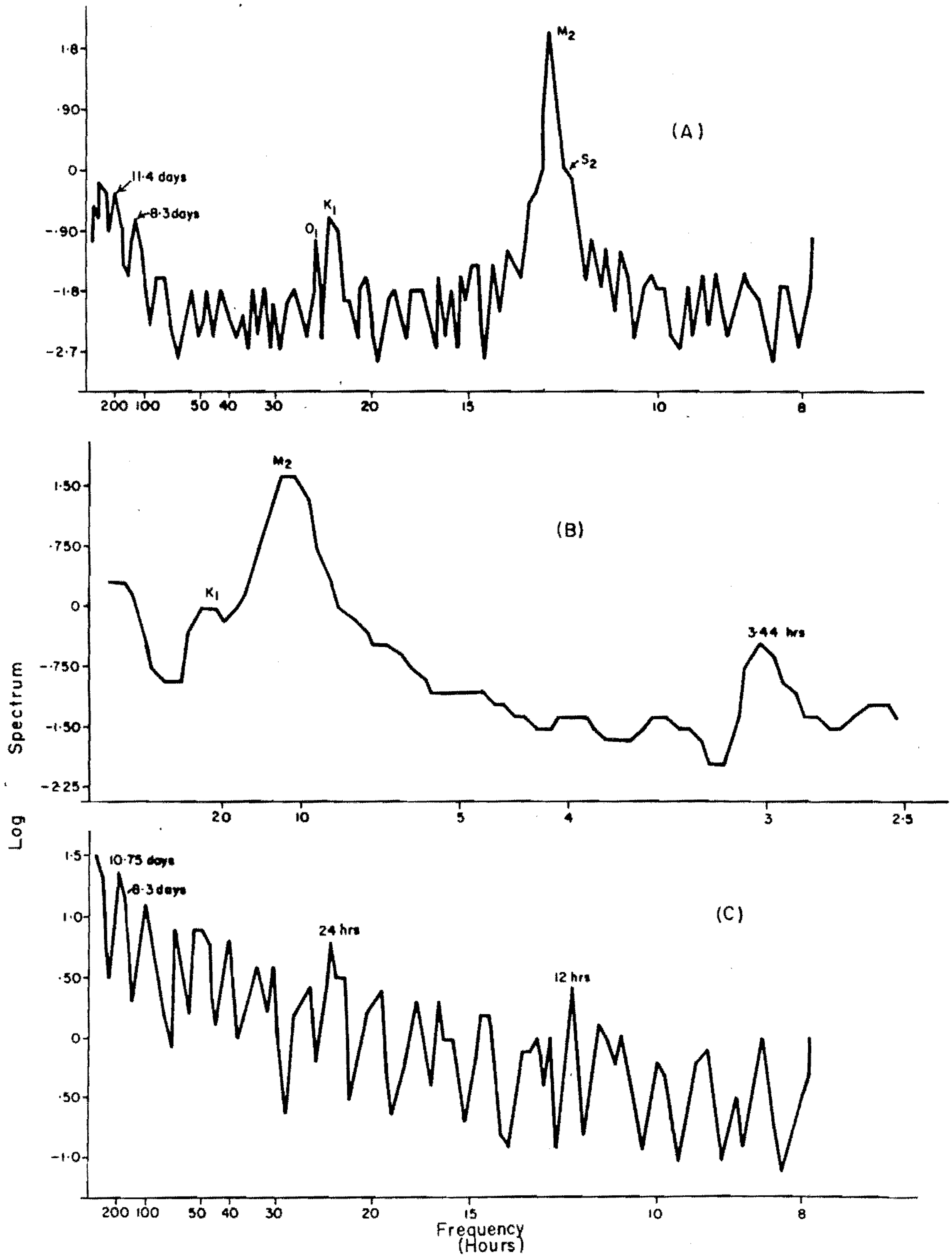


Figure 4.6 Spectral density graphs showing main tidal constituents and peak frequencies.
A. Long period tidal spectrum. Δt = 4 hrs.
B. Short period tidal spectrum. Δt = 15 mins.
C. Weather spectrum: Christchurch/Kaikoura pressure differentials. Δt = 4 hrs.

differentials between Christchurch and Kaikoura (see Figure 4.6C). These differentials are effective indicators of weather patterns along the east coast of the South Island, where a positive pressure differential with respect to Christchurch (pressure greater in Christchurch than Kaikoura) represents a southwesterly airflow along the coast, and a negative pressure differential represents a northeasterly airflow along the coast. The effect of these weather patterns is examined in the following section (4.2.1.1). Although Defant (1961; p.245) states that tides are only occasionally disturbed by atmospheric processes, there are no other tidal constituents with similar periods to this 'weather peak' in the spectrum. A slightly lesser peak at 8.3 days confirms a water-level weather component in the commonly referred to "5 to 10 day weather cycle" for New Zealand. Two papers, by Elliott and Wang (1978) and Smith (1978) also correlated meteorological effects with water level variations in two different estuaries. They found that local wind stresses generated fluctuations due to Ekman effects and longitudinal seiching with periods ranging from two to six days and up to 20 days.

Unfortunately, the version of the spectral analysis programme available did not provide for computation of statistical confidence bands around the spectral density curves. Therefore no statistical confidence limits can be applied to the peaks in the diagrams. However, in the context of the study, the fact that associations can be made between water level records and variables other than the normal tidal constituents is an important point.

Two peaks are clear in Figure 4.6B, in the short period

Table 4.2 Spectral density values from analysis of tidal water levels.
A. Long period Spectrum. Δt = 4 hrs.
B. Short period Spectrum. Δt = 15 mins.

	Tidal Component	Relative Power Density	Period (Hours)	Origin
A.	M_2	98.23	12.42	Principal lunar tide
	S_2	0.6990	12.00	Principal solar tide
	K_1	0.2238	23.93	Declinations of sun and moon
	O_1	0.0901	25.82	Lunar declination
	M_f	0.2840	327.87	Lunar fortnightly (spring and neap)
		0.3946	273.97	Weather forcing
		0.1425	199.01	Weather forcing
B.	M_2	39.98	12.42	Principal lunar tide
	K_1	0.9582	23.93	Declinations of sun and moon
		0.3215	3.44	Continental edge wave oscillation

spectrum. The main peak is again M_2 while the second has a period of 3.44 hrs. Table 4.2B lists relative power densities for this spectrum, and while the absolute values are different to those in Table 4.2A, the orders of magnitude are comparable. The origin of the 3.4 hr peak, visible as a frequent protuberance on the tidal record in Figure 4.4, probably derives from continental edge waves inducing oscillations within the harbour. Heath (1976c, 1979, 1982) reports the existence of oscillations in Lyttelton Harbour with a 2-3 hr period which he attributes to edge waves. The period is too long for oscillations due to normal harbour resonance, and Heath (1979) demonstrates that, (i) it is not phase-locked to the tides, and (ii) it does not represent the Helmholtz mode of oscillation which for Lyttelton has a period of about 2.2 hrs. He suggests that Banks Peninsula is a reflection point (antinode) for a standing edge wave, which would explain the very pronounced amplitude of the oscillation in Lyttelton. Heath notes that the period of the oscillation, visually around 2.5 hrs, has a broad spectral peak with a 3 - 3.2 hr period frequently apparent. This is presumably associated with a 3-4 hr quarter-wave resonance of the continental shelf in Pegasus Bay (Heath, 1979).

The 3-4 hr spectral peak located in this study is in close agreement with Heath's findings. The power density in this peak is of the same order of magnitude as the K_1 tidal constituent, and Heath (1979) postulates a weather correlated origin for the driving mechanism of the oscillation. Clearly both the edge wave oscillation, and weather patterns are of some importance to Lyttelton Harbour and its currents. The degree of influence of these two variables will be examined shortly.

It is appropriate at this juncture to examine some inherent problems with the spectral analysis programme utilized. Where long or short period tidal components are left out at either end of the spectrum frequencies the power within them is, "folded back", into the spectrum, overlapping onto and reinforcing other peaks. Caution should be exercised in interpreting the spectrum limits therefore, and where peaks exist close to, or at spectrum extremities they have been ignored in this interpretation. Extremity peaks are frequently lost or reduced when sampling intervals are altered.

The programme output for each run provides analysis from three bandwidths, of which the wider two provided insufficient detail for interpretation. Narrow bandwidth estimates of the spectral density, used here, supply a detailed picture of the spectrum but are vulnerable to sampling variability (Thrall and Engelman, 1981). Thus, peaks in the spectrum tend to shift in frequency depending on the sampling interval used in the data. Here again one must compromise. The sampling interval must be large enough to allow anlaysis of the longer period tidal components, but small enough to provide an accurate representation of the tidal wave. Hence the selection of a 4 hour interval in the foregoing analysis.

Spectral analysis using various sampling intervals will also alter the relative magnitudes of power density for the various component peaks. The spectra for sampling intervals of 6, 10, and 12 hrs from the same data are shown in Appendix 2. Despite the emphasis on components shifting it is apparent in all cases that weather forcing is significant, and it must therefore be regarded as a measurable influence on the water levels and hence on the hydrography and circulation in Lyttelton Harbour.

4.2.1.1 Tidal Variability, Weather Forcing, and Edge Wave Oscillation

Following the above analyses and results, the existence of a correlation between weather, edge wave oscillations, and tidal variability (flood and ebb durations) was further examined using the two month record discussed in section 4.2. Since a relationship had been established between weather, edge wave oscillations, and tides from spectral analysis, normal tidal constituents were not removed from the tide curve as was done in section 4.2. Instead variability was expressed as the ratio of the duration of flood tides (t_f) to that of ebb tides (t_e) and plotted as a curve in Figure 4.7B. From this it can be seen that there is considerable variation in the relative duration of corresponding ebb and flood tides. It is again notable that flood tides are predominantly longer than ebb tides although no short term systematic pattern exists.

The plot in Figure 4.7A shows 12 hourly mean differences in barometric pressure (QNH) between Dunedin and Christchurch for the same two month period. The relevance of these data lies in the fact that tides flood from south to north on the east coast of the South Island and ebb in the opposing direction. Thus a positive value in Figure 4.7A (pressure greater in Dunedin than Christchurch), reflects a south-westerly airflow (McKendry, 1985) and could be expected to augment the duration of the flood tide; and *vice versa* for the ebb where negative values indicate a north-easterly air-

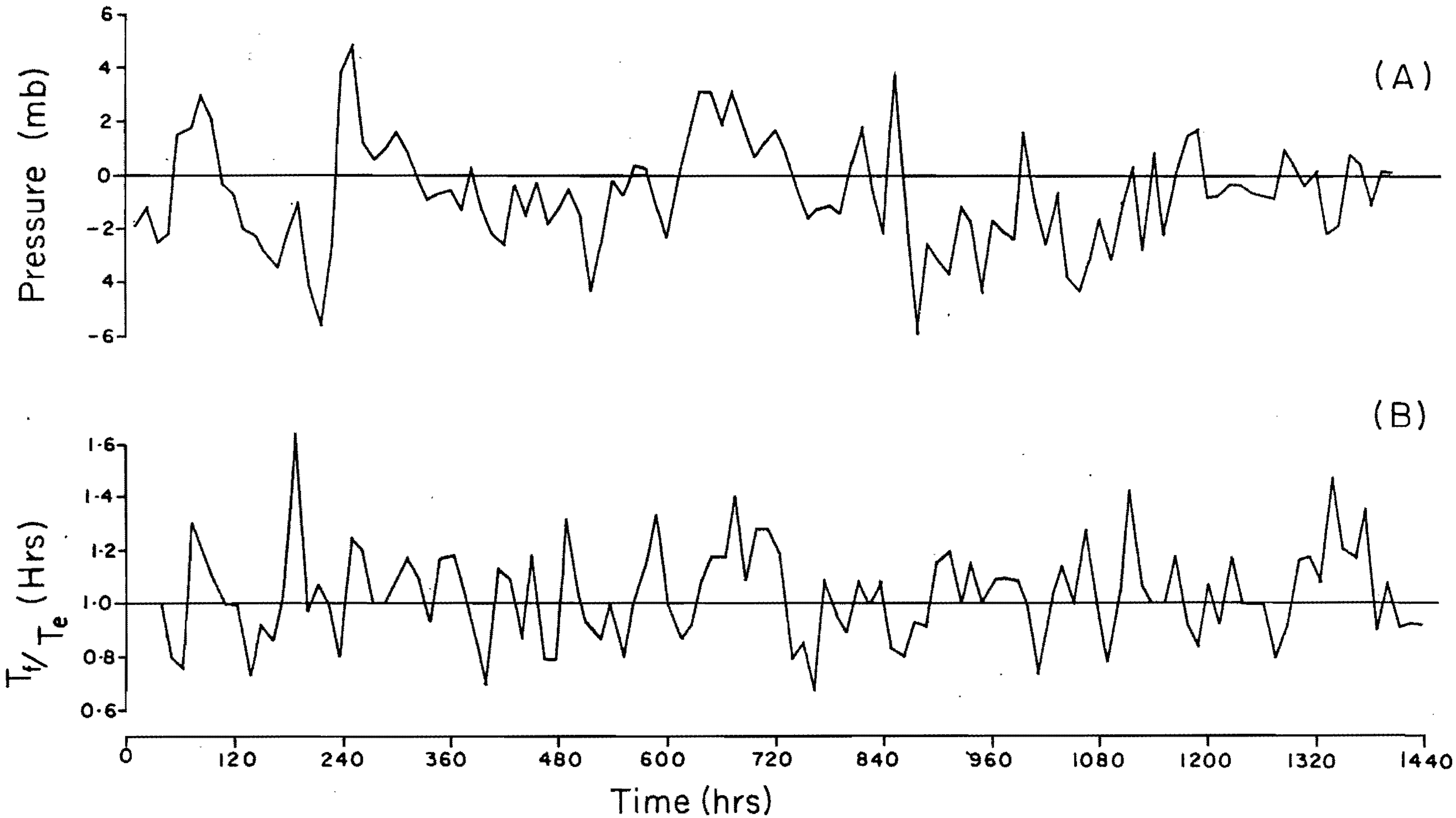


Figure 4.7 Graphs of QNH pressure differentials and tidal variability.
A. Dunedin pressure minus Christchurch pressure plotted in 12 hrly means.
B. Plot of the ratio duration of flood tides/duration of ebb tides.

flow. In a study of South Island synoptic scale atmospheric circulation, based on daily surface isobaric charts, Sturman et al. (1984) found the most frequent airflow over a 20 year period was anticyclonic, southwesterly. On the basis of the above argument, this supports the finding that flood tides are predominantly longer than ebb tides at Lyttelton.

There is no overall, direct correlation between the two curves, 4.7A and B. However certain portions of the curves correlated and it was considered that a degree of similarity existed in the level of variance in positions of peaks and troughs over the short period. On this basis, and as sampling intervals were approximately equal, 12 hrs for pressure and 12.48 hrs (average duration of a cycle) for tidal variability, cross-spectral analysis was performed on the two data sets. Results in Figure 4.8A and B show spectral density plots for pressure and tidal variability respectively. They are similar in shape and almost identical in peak frequencies for the higher frequency half of the curves. Figure 4.8C illustrates coherence between the curves in 4.8A and B, with tidal variability specified as the dependent variable. Coherence is a measure of linear association between the two variables similar to squared correlation (Thrall and Engleman, 1981). In this case it shows two important peaks at approximately 78 and 57 hr frequencies with coherence values of 0.855 and 0.758 respectively. Phase differences between the two sets of data at these frequencies correlate tidal variability with pressure changes 50 and 96 hrs beforehand respectively. Thus variability in the relative duration of flood and ebb tides occurring at a 78 hr (3.25 day) cycle is strongly correlated to changes in weather patterns, south

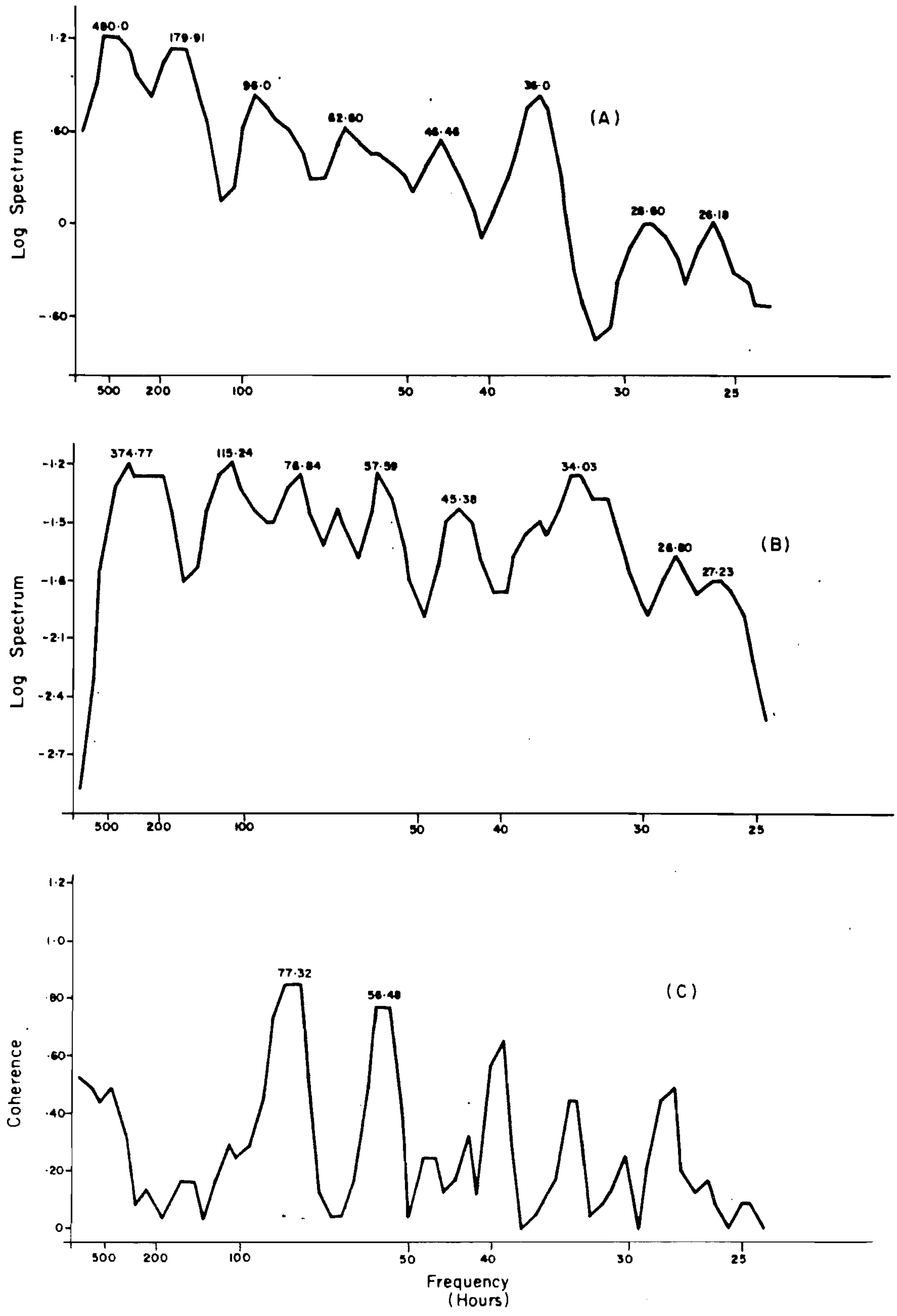


Figure 4.8 Spectral density and coherence graphs.
A. Pressure spectrum: Dunedin-Christchurch QNH - $\Delta t = 12$ hrs.
B. Tidal variability spectrum: Flood duration/Ebb duration. $\Delta t = 12.48$ hrs.
C. Plot of coherence, or linear association between A and B.
Numbers show peak frequencies in hours.

of Lyttelton, two days beforehand. To a lesser extent this is so for the 57 hr variability peak and weather changes four days prior. Other coherence peaks either had phase lags of the incorrect sign or with low association values.

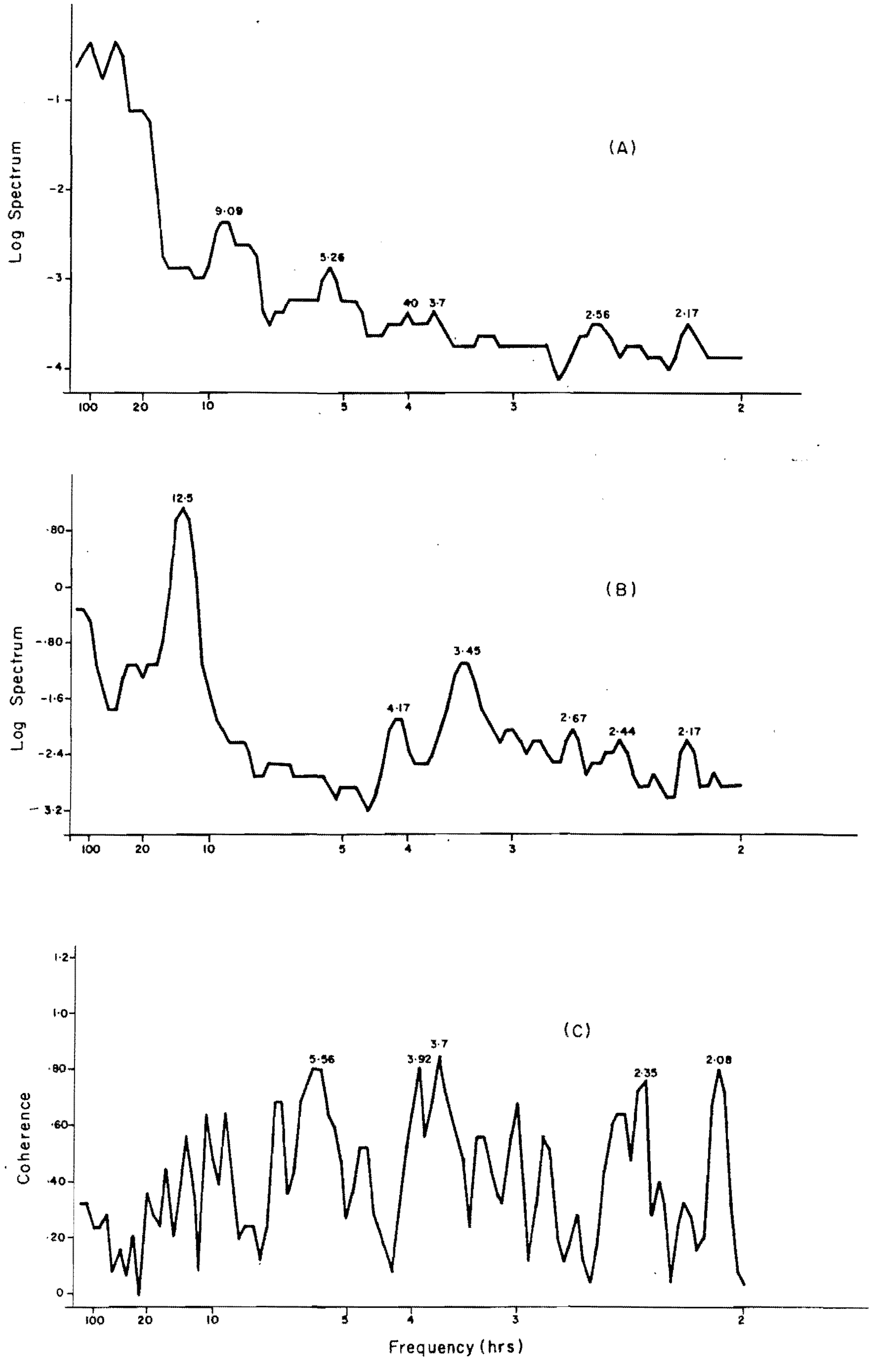
This obviously fails to account for much of the short term variation occurring in the space of several tidal cycles. A further cross-spectral analysis was therefore computed between tidal elevation data and flood/ebb duration data for a week, with a sampling interval of one hour. The latter data were obtained from a plot of ratio values joined by straight lines as in Figure 4.7B. Although both sets of data were obtained from the same record and as such were not independent, their presentation units of measurements (metres and hours (as ratio data)) and their plotted curves, were quite dissimilar.

Results in Figure 4.9A, B and C show maximum coherence between the two spectral plots at short term frequencies less than six hours, most of which lies between two and four hours. This interval correlates well with Heath's (1979, 1982) 2 - 3.5 hr edge wave oscillation, and the maximum coherence value of 0.821 at 3.7 hrs frequency is in excellent concurrence with the 3.45 hr oscillation peak in Figures 4.6B and 4.9B. It is concluded from these analyses that tidal variability is caused predominantly by a combination of edge wave oscillations and weather forcing. Their effects on currents and circulation will be discussed subsequently.

4.2.2 Tidal Currents

A consequence of the effect of tidal asymmetry in estuaries, discussed by Defant (1961), McDowell and O'Connor (1977), and others, is that flood tide velocities are greater

Figure 4.9 Spectral density and coherence graphs.
A. Tidal variability spectrum: Flood duration/Ebb duration. $\Delta t = 1$ hr.
B. Tidal spectrum. $\Delta t = 1$ hr.
C. Plot of coherence, or linear association between A and B.
Numbers show peak frequencies in hours.


(A)
Log Spectrum
-1
-2
-3
-4
9·09
5·26
4·0
3·7
2·56
2·17
100
20
10
5
4
3
2
(B)
Log Spectrum
·80
0
-·80
-1·6
-2·4
-3·2
12·5
4·17
3·45
2·67
2·44
2·17
100
20
10
5
4
3
2
(C)
Coherence
1·2
1·0
·80
·60
·40
·20
0
5·56
3·92
3·7
2·35
2·08
100
20
10
5
4
3
2
Frequency (hrs)

than ebb velocities but of shorter duration. The further up the estuary the tidal wave travels the greater the distortion and asymmetry, and by inference the greater the deviation between flood and ebb tide current velocities.

Current data were obtained from 12 tidal stations established around Lyttelton Harbour, and are shown in Figure 4.10. These were monitored for periods ranging from 10 hrs to eight tidal cycles. Additional flow information was obtained from a number of minor sites which were occupied at irregular intervals for around 15 mins, primarily to acquire directional data. Position fixing for current stations was achieved using sextant and compass bearings. Instrumentation at stations 1 and 2, and at minor sites, consisted of a Savonius rotor suspended by cable from a launch anchored fore and aft. Velocity and direction at stations 1 and 2 were recorded every 15 mins at 1 m above the bed, and at mid-depth and on the surface every 30 mins. All readings were averaged from a visual display over a 120 second period.

Data from stations 3-12 were collected by the Lyttelton Harbour Board in 1973 (referenced in Bushell and Teear, 1975). Instrumentation was an Ono, self-recording, propeller type current meter moored at between 1.5 and 1.8 m above the bed by means of a submerged buoy. This provided a continuous record of both velocity and direction for up to four days with data being averaged over 15 min intervals. In some instances equipment failure caused an incomplete record so that current asymmetries could not be considered, but at all sites a clear record of velocity and direction for both ebb and flood flows was obtained.

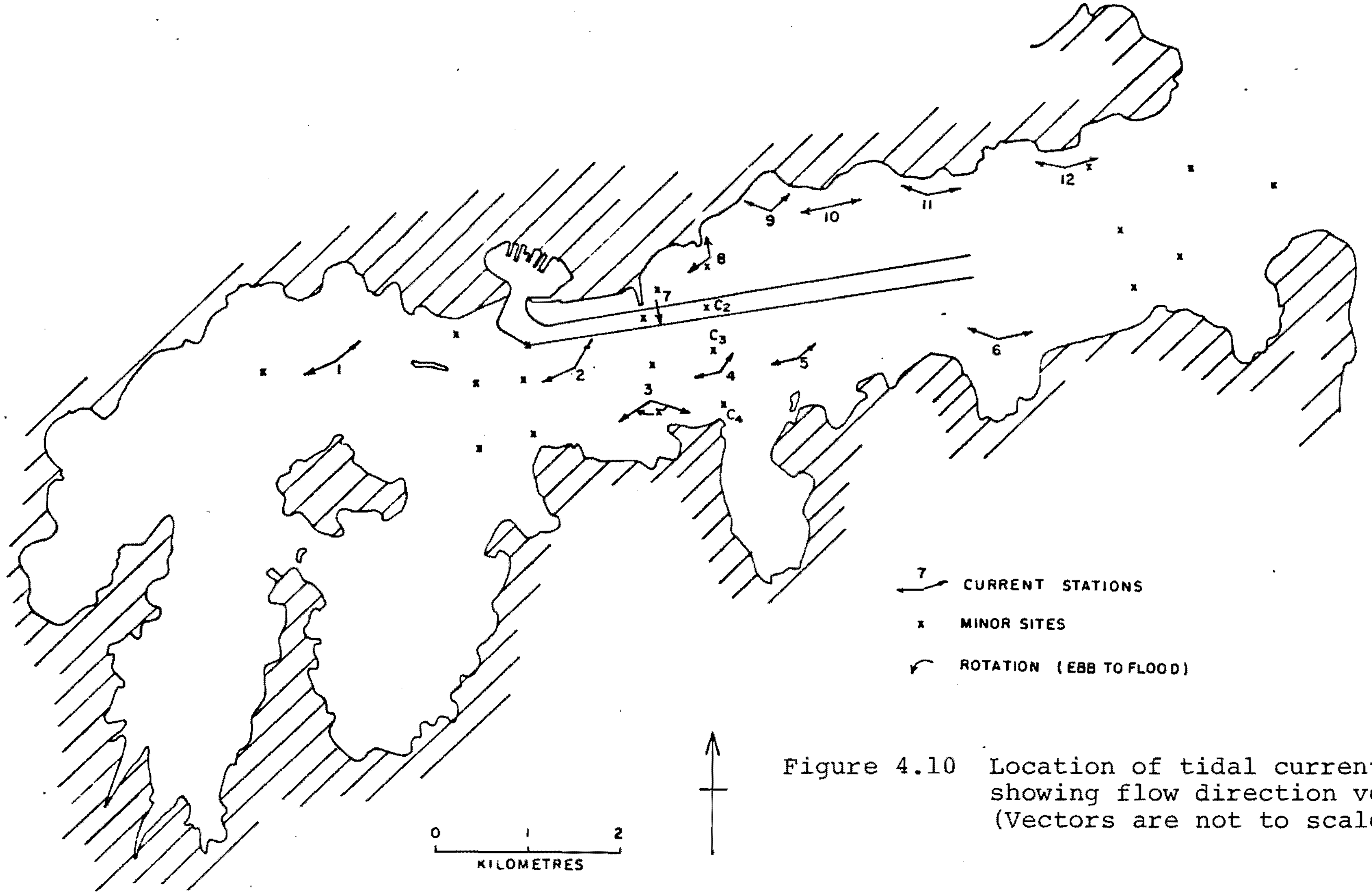


Figure 4.10 Location of tidal current stations showing flow direction vectors. (Vectors are not to scale.)

A major consideration when obtaining data in a wave affected environment is the effect of wave-induced oscillatory currents on the recording equipment. Hammond and Collins (1979) established that there is an inherent tendency for all current meter impellers to give indicated velocities higher than the actual current velocity when in the presence of wave energy. They found these errors to be greatest when the maximum velocity of the wave-induced orbital motion exceeds the velocity of the current, and that Savonius type rotors give greater overreading errors than meters using propellers. Accordingly, measurements using the Savonius rotor were taken only during calmer conditions. No information was available on the sea state at the time the Ono recordings were obtained. However, the velocities are slightly higher overall than those obtained using the rotor. This may well be due to wave influences, particularly at stations 11 and 12 which are exposed to swell generally evident at the harbour entrance. A further factor potentially increasing recorded Ono meter velocities is the submerged buoy mooring, which will itself become mobile under wave activity in shallow water. The effect is less with submerged rather than surface buoys and is examined by Gould and Sambuco (1975).

Table 4.3 provides a breakdown of velocity data for the 12 main stations. Average velocities for flood and ebb flows are 0.23 and 0.22 ms^{-1} respectively. Little difference is evident between spring and neap tide velocities; recordings at stations 1 and 2 on a spring tide being particularly low although they were not obtained over a full tidal cycle. High velocity currents are to be expected

Table 4.3 Tidal current data. Gaps in the table are where data are insufficient or unknown.

Station No.	Tide State	Flow	Velocity (ms^{-1})* Average	Max.	Average Duration (Hrs)
1	Spring	Ebb	0.13	0.33	
		Flood	0.19	0.43	
2	Spring	Ebb	0.14	0.25	
		Flood	0.16	0.25	
3	Neap	Ebb	0.22	0.42	6.74
		Flood	0.24	0.43	5.18
4	Spring	Ebb	0.23	0.58	6.05
		Flood	0.26	0.73	6.46
5	Neap	Ebb	0.23	0.46	5.71
		Flood	0.23	0.46	5.92
6		Ebb	0.18	0.38	
		Flood	0.27	0.53	
7	Neap	Ebb	-	-	-
		Flood	0.32	0.96	Continuous
8	Neap	Ebb	0.22	0.43	5.47
		Flood	0.16	0.27	6.34
9	Spring	Ebb	0.20	0.42	6.34
		Flood	0.18	0.34	5.81
10	Neap	Ebb	0.27	0.38	
		Flood	0.25	0.42	
11	Spring	Ebb	0.30	0.53	
		Flood	0.23	0.42	5.50
12	Neap	Ebb	0.28	0.61	6.48
		Flood	0.25	0.71	5.15

* Data from stations 1 and 2 at z = 100 cm (not continuous)

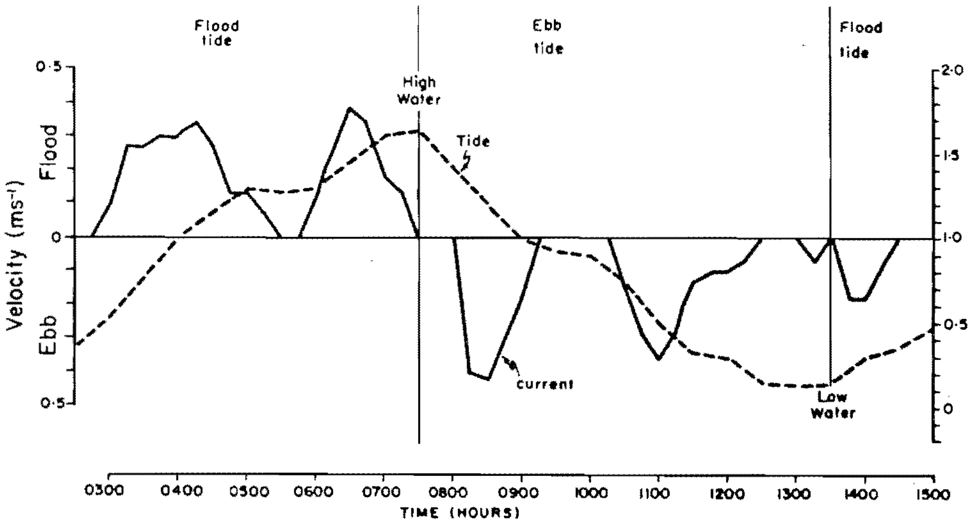
Data from stations 3-12 at z = 150-180 cm (continuous) at station 7 due to flow constriction by the breakwater which induces an eddy and a permanent flood current at this location.

Asymmetry exists in ebb and flood flows but varies considerably. Maximum flood velocities exceeded ebb velocities at only half the sites monitored. The times listed in Table 4.3 are average durations taken over the recording period while actual flow times for either flood or ebb currents varied between 4.08 and 8.1 hours for the 12 stations. Slack water periods are included in average duration times but these also varied. Commonly slack water occurs for 30 to 45 mins per tide either at the end of the flow or in the middle. Just as frequently it may be considerably less and occur only once in a complete cycle, as illustrated in Figure 4.11.

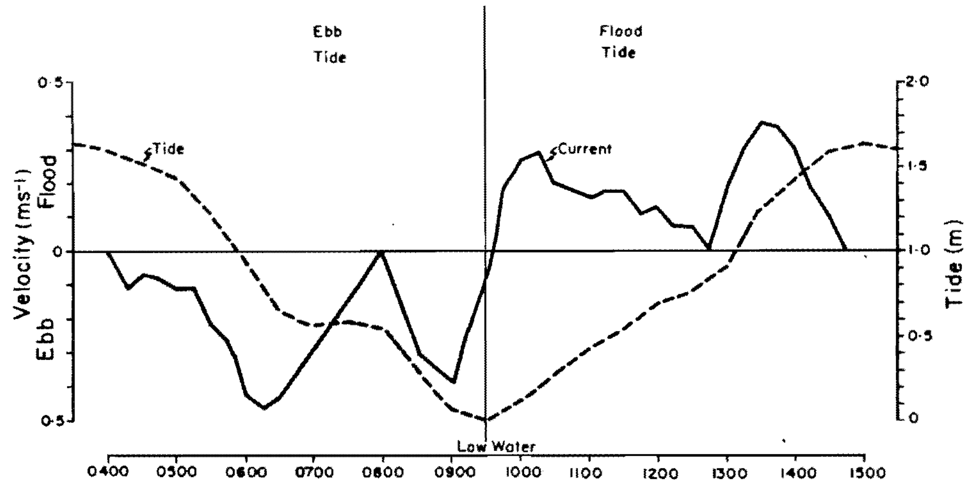
These data can be taken to indicate a predominant flood flow on the southern side of the harbour, and a predominant ebb flow on the northern side; a pattern consistent with horizontal circulation in well mixed, laterally inhomogenous estuaries (Dyer, 1973; Pritchard, 1955; Wicker, 1965). Stations on the south side exhibit flood currents of both greater duration and velocity than the ebb, and vice versa on the northern side. Exceptions to this pattern are the northern station 8, where the flood is longer due to the eddy caused by the breakwater, and the two southern stations, 5, where average ebb and flood velocities are equal; and 3, which has a longer ebb flow caused by a complex circulation pattern (refer section 4.3). Stations 1 and 2 were monitored for insufficient periods to examine flow times. However, flood velocities were higher in both cases.

Figure 4.11 Current velocity curves for four stations plotted against the tidal water level curve, showing velocity vs phase of the tide.

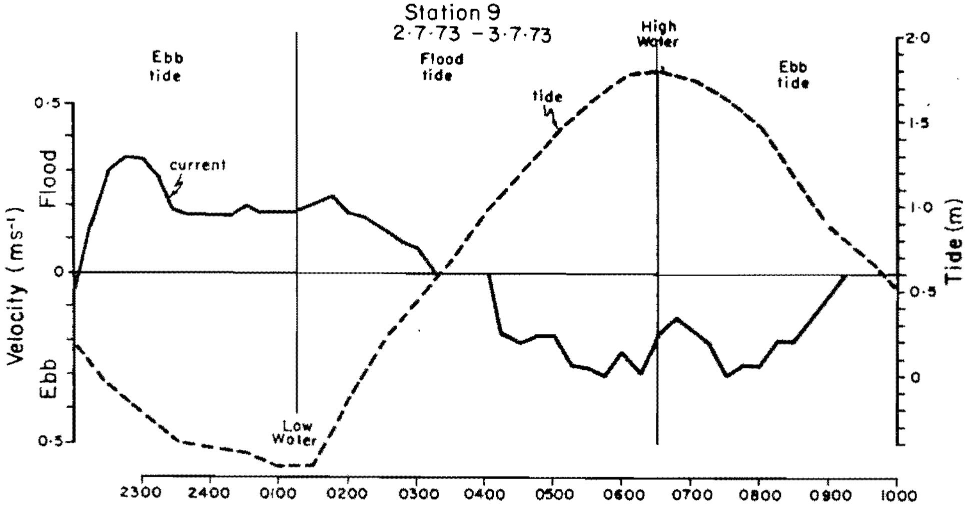
Station 3
19·6·73



Station 5
14·6·73



Station 9
2·7·73 – 3·7·73



Station 12
26·5·73 – 27·5·73

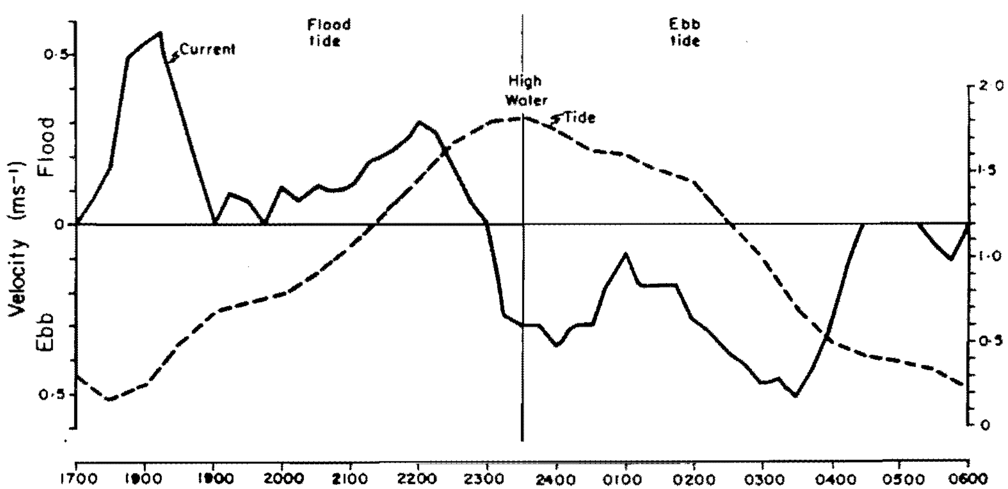


Figure 4.12A-D illustrates several velocity profiles recorded at minor sites with the Savonius rotor. As stated earlier these sites were monitored for short periods only, and the profiles do not represent instantaneous vertical velocities, being taken over a 5 min interval. The pattern shown in Figure 4.12D occurs most frequently for recordings at all locations where vertical profiles were obtained. Profiles 4.12A-C, at sites C_2 and C_3, are important however, as they are indicative of flow separation in the water column which is significant for circulation and therefore for overall hydraulic patterns. They are also comparable to vertical, flood velocity profiles for a partially mixed estuary (Pritchard, 1967a; Fig.3) which show minimum velocities on the surface, increasing with depth until near the bed where friction becomes important. Such profiles were not found to exist for average velocities across the flood tide at stations 1 and 2 where surface and mid depth velocities were 0.02 - 0.03 ms^{-1} faster than near bed velocities. Due to a lack of data throughout the water column vertical profiles were not obtained at stations 3-12. To overcome this and a lack of current data in the centre of the harbour, and to examine longitudinal and lateral dispersion, a dye tracing experiment was conducted.

4.2.2.1 Dye Tracing To Determine Dispersion, Mixing, and Flow Paths

Dye tracing has been used extensively in river flow studies but has found fewer applications in estuaries and inlets. Parnell (1981) used the technique quantitatively with rhodamine WT to measure estuarine exchange processes,

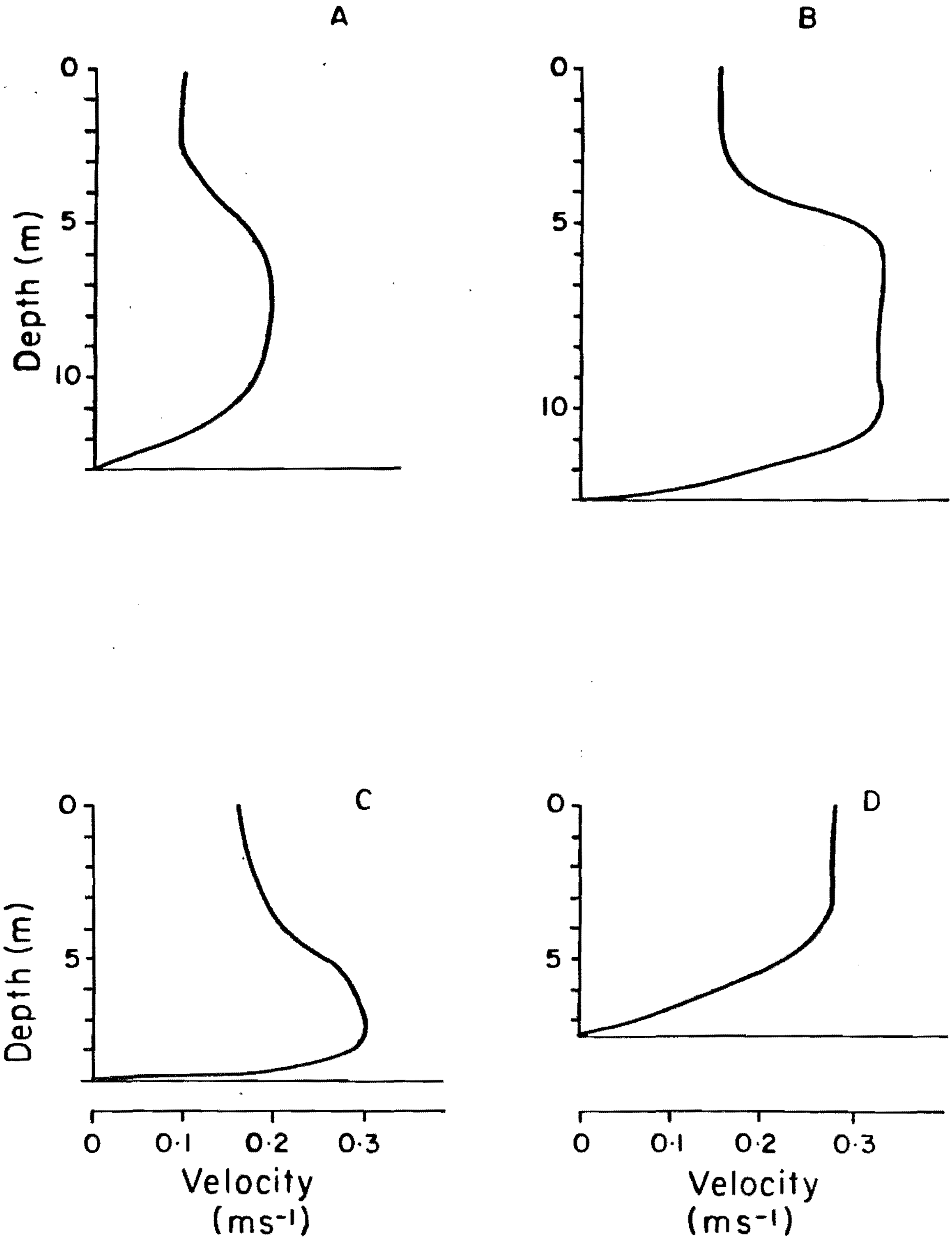


Figure 4.12 Current velocity profiles taken over 5 min. intervals.
A: Site C_2 - commencement of flood tide.
B: Site C_2 - mid flood.
C: Site C_3 - mid flood.
D: Site C_4 - mid flood.

and Pritchard and Carpenter (1960) traced rhodamine B for five days in an estuarine/harbour environment to observe water dispersion. In Lyttelton Harbour Garner and Ridgway (1955) monitored surface trails of fluorescein from which, in conjunction with float tracking, they were able to define the order of magnitude of tidal streams.

The experiment carried out in this study was a qualitative one to examine the degree of dispersion occurring within the harbour during the course of a day, (two tidal cycles) and to establish flow paths in the centre of the harbour and flow profiles throughout the water column.

Method:

The dye selected for this study was rhodamine WT, specifically designed for water tracing. Parnell (1981) found this to be the most suitable tracer in terms of preparation, detectability, background levels, toxicity, and loss in the environment by adsorption and decay. Minimum detectability using a Turner III filter fluorometer is 0.013 $\mu g l^{-1}$ (Smart and Laidlaw, 1977), or 0.002 parts per billion (ppb) (Pritchard and Carpenter, 1960). In this case a filter fluorometer was unavailable and instead an Aminco-Bowman spectrofluorometer was utilized. Smart and Laidlaw (1977) found spectrofluorometers were comparable in sensitivity to the Turner III and more specific. Instead of using broad spectrum filters, dials are set precisely to the excitation and emission wavelengths which are 555 and 580 nm respectively for rhodamine WT. In all analyses conducted using this fluorometer 2 mm light slits were in place.

Prior to releasing the dye water samples were obtained at the bottom and surface to assess natural background levels. These were negligible. Calibration curves were drawn from the fluorometer to be used for dye concentrations and percentage loss of fluorescence with salinity, and are presented in Figure 4.13A and B. Although the experiment was qualitative, relative dye concentrations were used to establish the main flow paths and uniform decay of dye was desirable for all locations within the harbour. Parnell (1981) and Smart and Laidlaw (1977) indicated that a salinity calibration curve should be drawn for every separate batch of rhodamine WT as effects were found to vary considerably over a number of experiments. It is apparent from Figure 4.13B that salinity would not be an influential factor over the narrow range of salinity which exists in the harbour.

The injection site selected was in the centre of the harbour opposite Purau Bay, on the south stakes line of the channel (Fig. 4.14). The site was chosen to be near the channel where current data were lacking, sufficiently distant from the harbour entrance to prevent loss of dye on the ebb tide, and central to the overall harbour length. Dispersion throughout the water column was of interest, particularly that associated with near-bed currents since these presumably reflect sedimentation patterns, so the injection strategy involved the release of dye near the seabed. This was accomplished by siphoning the dye down a 12 mm diameter plastic hose to the outlet 45 cm above the bed.

Ten litres of stock rhodamine WT, diluted to 30% by volume to aid siphoning and dispersion, were released at an

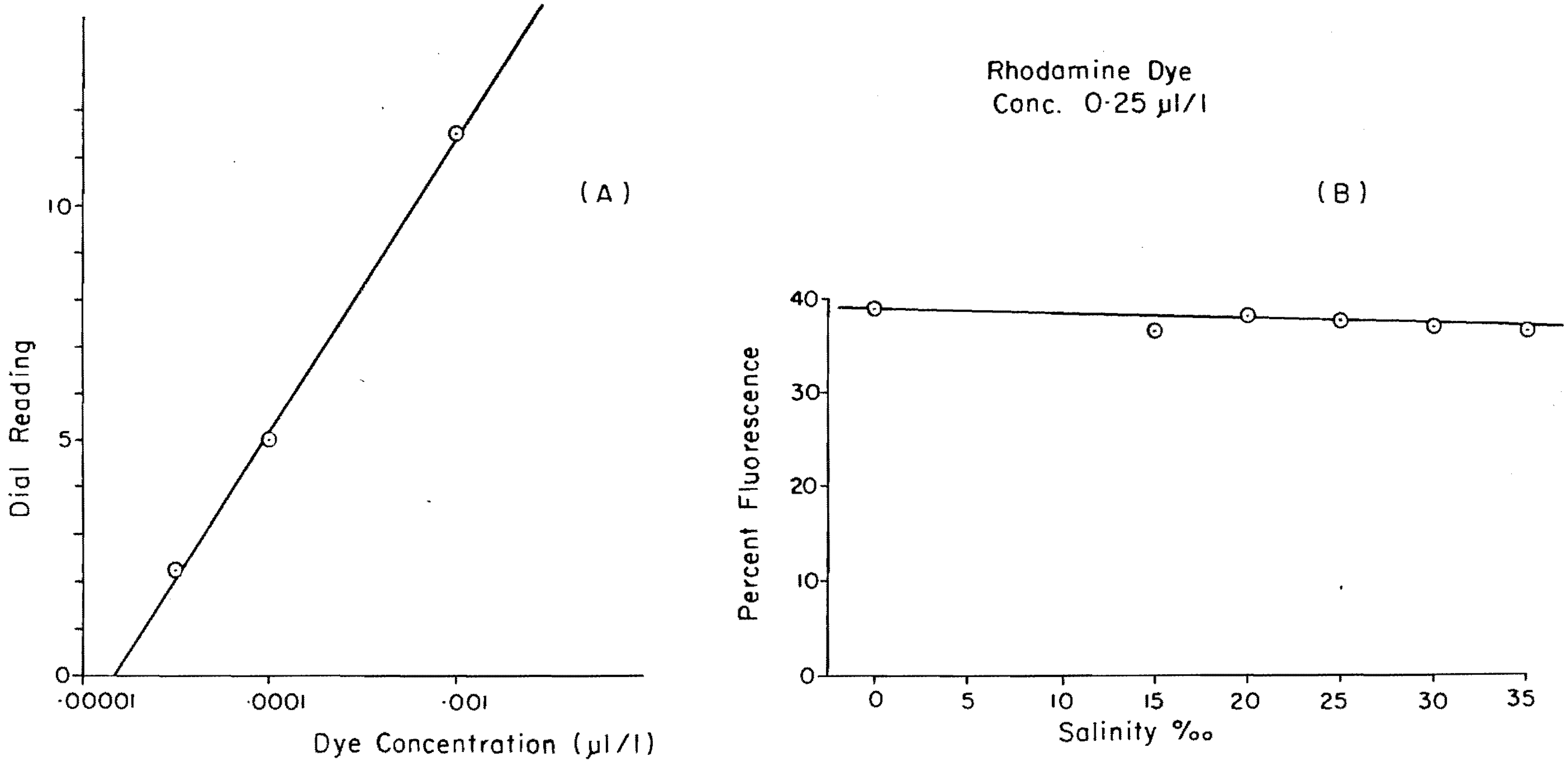


Figure 4.13 A. Calibration curve for Rhodamine WT.
B. Loss of fluorescence in Rhodamine WT with salinity.

approximate rate of 1.96 litres$\cdot$min^{-1}. Stock rhodamine WT is supplied as a 20% solution by weight with a specific gravity of 1.15 (Parnell, 1981), which amounts to 2.3 kg of dye released; (specific gravity of seawater is approximately 1.07). The injection was on 12 July 1983 on a spring tide at midday, predicted low water.

Figure 4.14 shows the grid sampling pattern from which point samples were taken at four levels, 0.2, 0.4, 0.6 and 0.8 depth from the bed upwards, using a model SD 1.5 litre sampler constructed by Scott Technical Instruments Ltd, Kaiapoi, New Zealand. This is a free-flushing sampler, collecting an instantaneous sample by trigger mechanism released with a traveller sent down the cable. Sampling commenced at the western end of the grid at 0915 hours on 13 July on the ebb tide, approximately 1.75 tidal cycles after the injection. Due to the size of the area covered and the slow launch speed, sites 1-24 were sampled on the ebb tide, and 25-40 on the flood. Sites 1,2,3 and 17 were not sampled at the 0.6 depth because of shallow water, and sites 37-40 were sampled only at the 0.2 depth. Sixty ml samples were removed from the sampler and stored in plastic jars in darkness to prevent photochemical decay prior to analysis the following day. The sampler was squirted with distilled water after every site in order to reduce possible contamination between samples. Conditions remained calm throughout the experiment.

Results:

A potentially important source of analytical error in this experiment, particularly with the bottom samples,

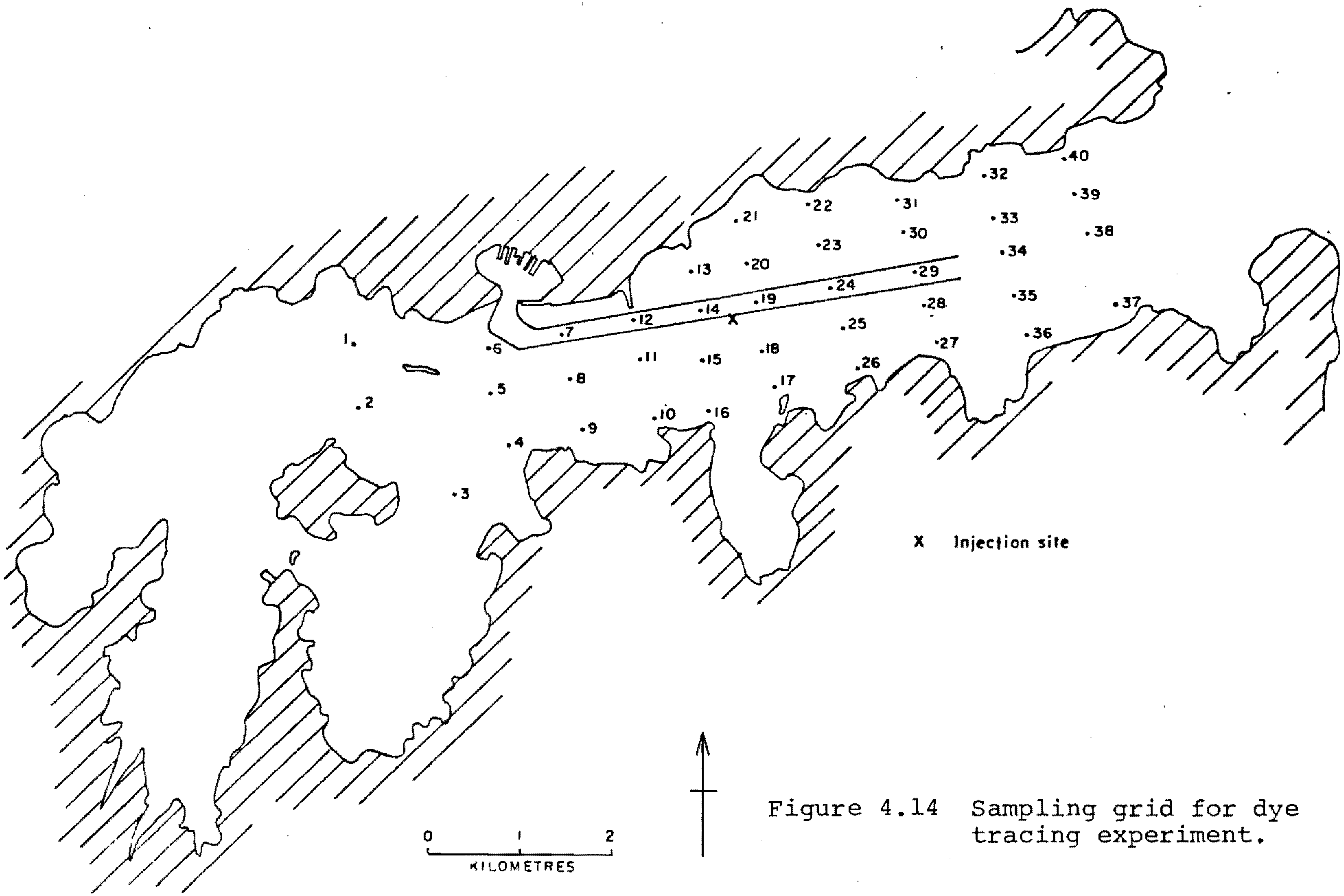


Figure 4.14 Sampling grid for dye tracing experiment.

arose from the presence of suspended sediment. Scott, Norman and Fields (1969) and Smart and Laidlaw (1977) report that the presence of suspended sediment can raise apparent background fluorescence and reduce effective dye fluorescence because of light absorption and scattering. Substantially correct results could be obtained if suspended sediment was allowed to settle for 10 to 20 hours. The error becomes increasingly greater with a corresponding decrease in dye concentration to low levels such as those found in this instance. Accordingly all samples were allowed to stand for 17 hours prior to analysis and removal of a small quantity of water for analysis was from the surface by means of a fine pipette. It was found that without care an apparent background level of 0.05 ppb ($x10^9$) could be readily induced. As an additional control therefore, suspended sediment samples were obtained simultaneously with the 0.2 depth dye samples. Suspended sediment contours for this depth are shown in Appendix 3 and bear no resemblance to the dye contour patterns.

Figures 4.15A-D illustrate dye dispersion at the four depths over the sampling period. Contour lines are interpreted as representative of the main tidal flow paths where maximum quantities of dye have accumulated. Where dye was found concentrations were low, ranging from 0.051 to 0.097 ppb, but they nevertheless provided a useful picture of flow.

In agreement with directional current data and accepted theory the ebb dye trail tends towards the northern side of the harbour, moving obliquely across the channel from the south. Flow at the 0.2 and 0.4 depths is oriented somewhat more along the line of the channel than the surface water. At the head of the harbour the tide ebbs around both sides of

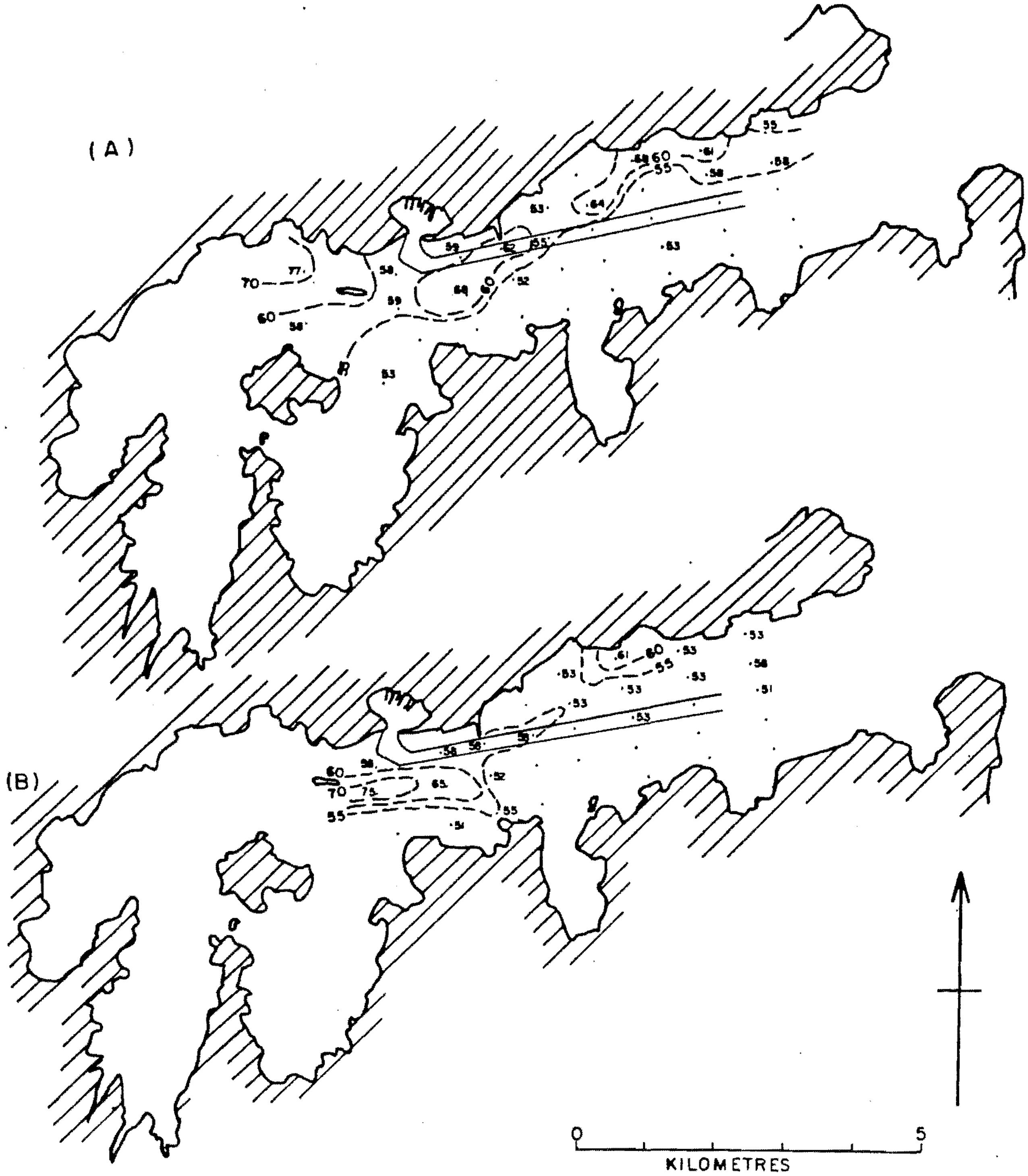


Figure 4.15 Dye dispersion contours. Concentrations in $\mu l/l \times 10^{-6}$

A. Sample depth - $Z/Z_o = 0.8$

B. $Z/Z_o = 0.6$

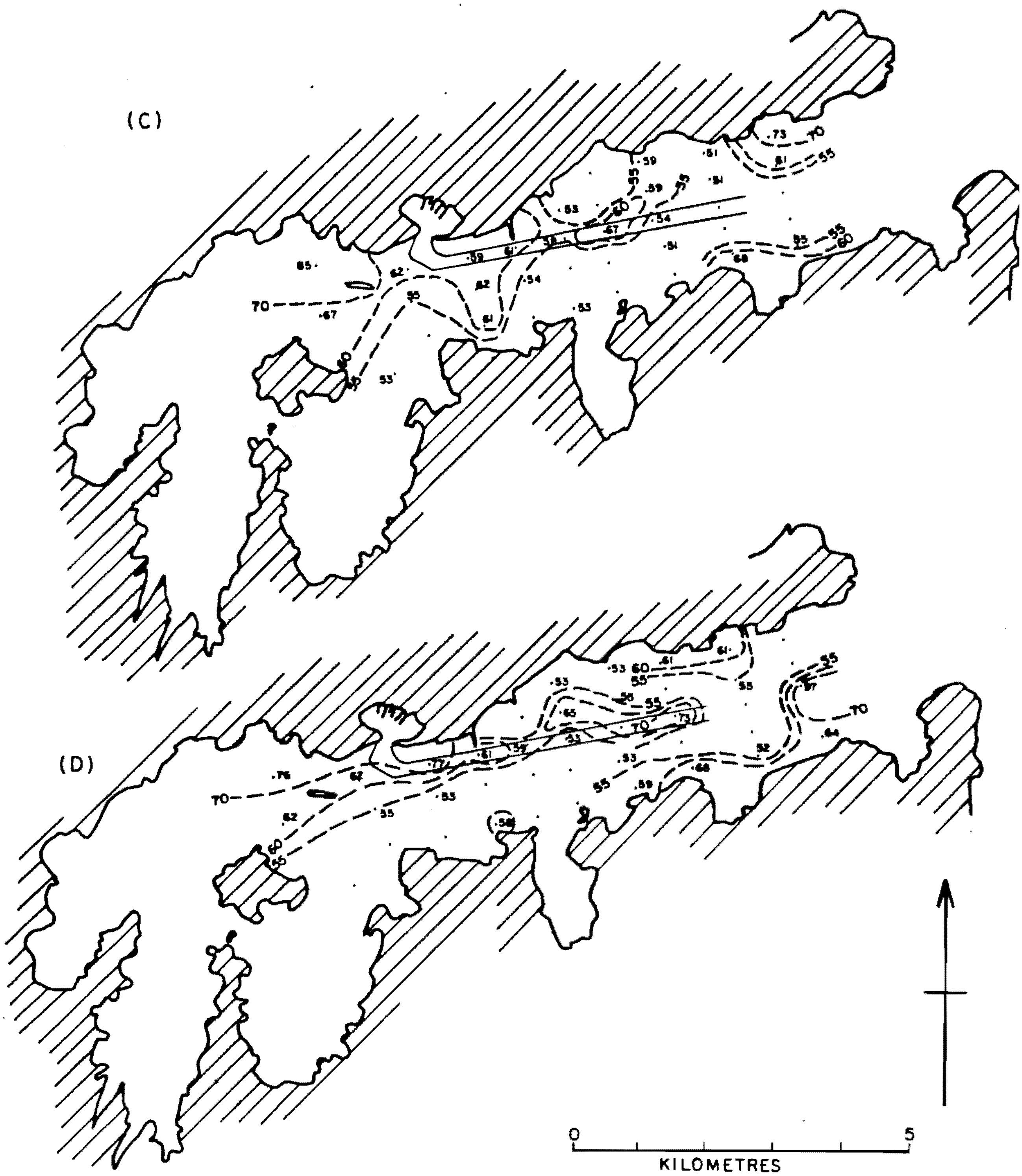


Figure 4.15 continued.

C. Sample depth – $Z/Z_o = 0.4$

D. $Z/Z_o = 0.2$

Quail Island but is again dominant on the northern side. The pattern is partially reversed in the narrow harbour section in the mid 0.4 and 0.6 depths where flow is initially forced toward Diamond Harbour before moving across to the north. Such a pattern is indicative of layered flow which was also observed on the ebb tide by Garner and Ridgway (1955; Fig.5) near Breeze Bay and Little Port Cooper using floats and drogues. The location of layered flow established from this experiment is of some interest as it occurs in the narrowest section preceding oblique harbour flow. Oblique flow tends to suggest a Coriolis force influence which would also increase relative ebb velocities on the north side, a phenomenon already established for Lyttelton. However Coriolis force is regarded as a significant influence only in inlets of large dimensions, e.g. the Persian Gulf (Glen, 1979). In this instance the layered flow coincides with the established salinity 'transition zone' between upper and lower harbours and oblique flow occurs only within a short distance from the breakwater. Rather than Coriolis, these two facts suggest more an implicit relationship between tidal currents and harbour topography or geometry.

Flood tide traces of dye are also indicative of Coriolis force and topographically induced circulation. Figures 4.15C and D both depict a flood current crossing the harbour obliquely inside the entrance, augmented by further flow parallel to the harbour axis in the centre and on the northern side. Oblique flow again occurs only within a limited distance before becoming parallel flow. It could well be argued that flood tide patterns merely represent lag ebb tide dye traces. However sites 31-40 were sampled from 2 - 2.5 hrs after predicted low water, and little dye was found on the

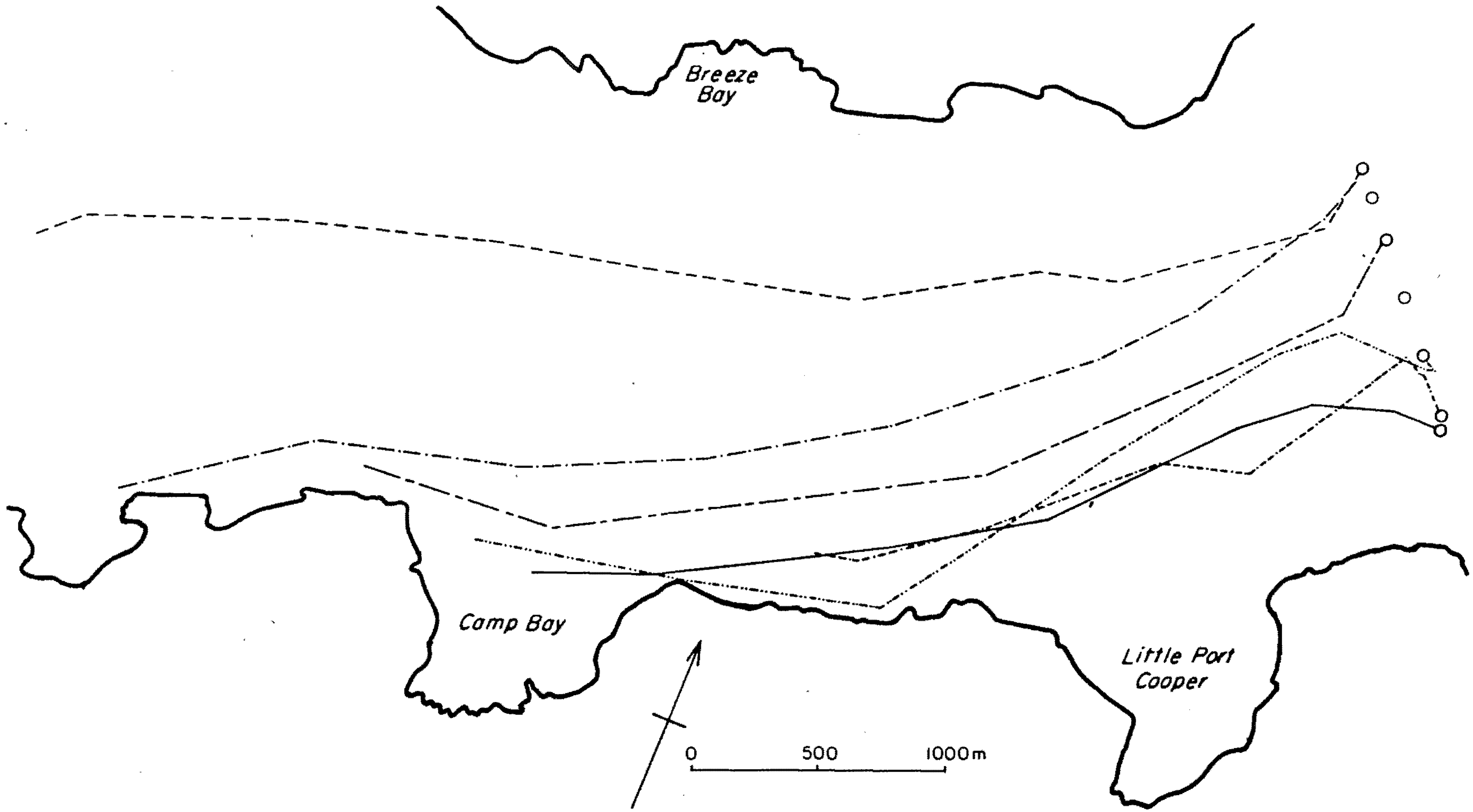


Figure 4.16 Flood tide flow paths through the harbour entrance. Data were obtained by the Lyttelton Harbour Board from surface float tracking.

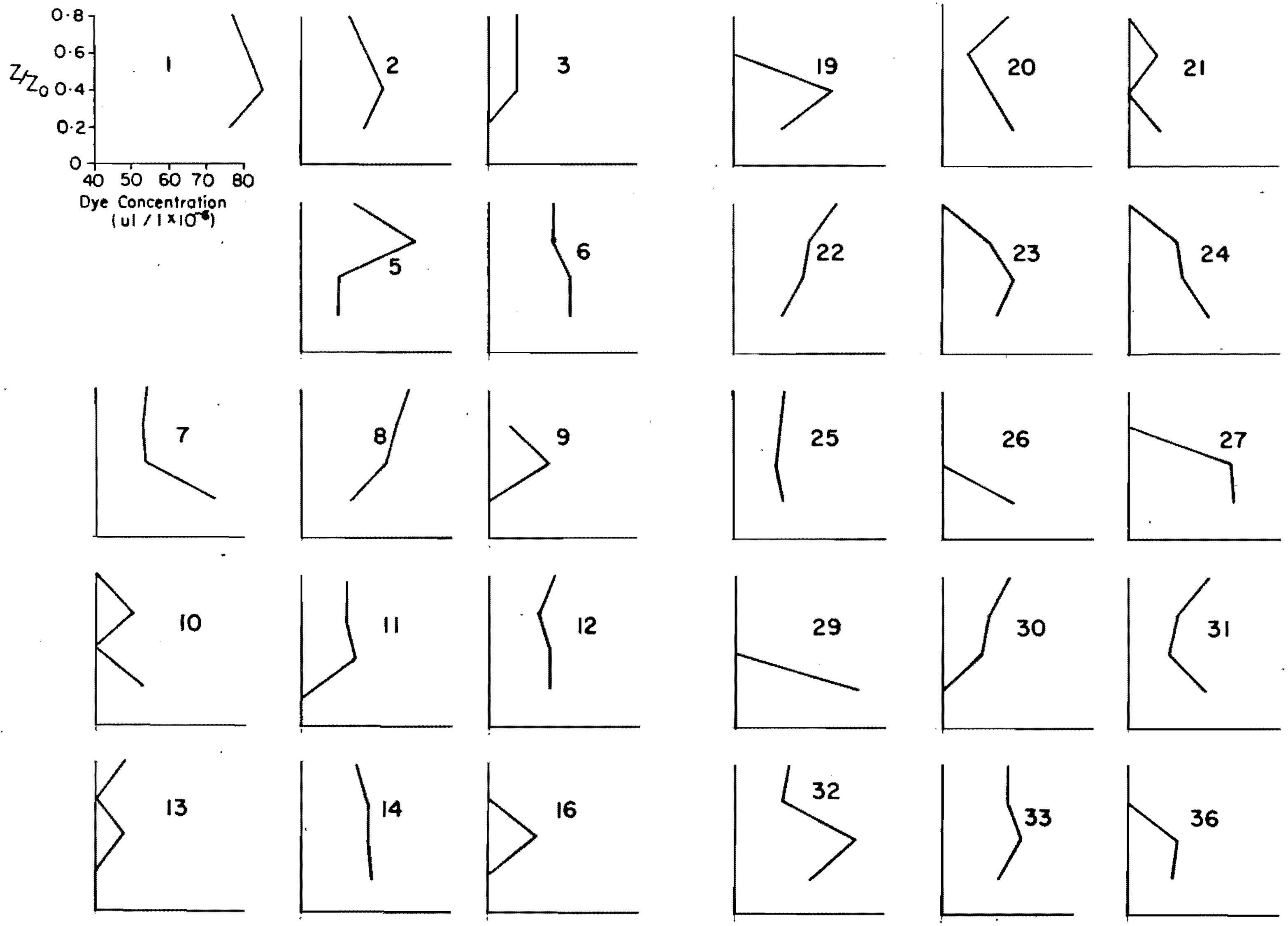
southern side on the ebb tide. It is difficult to assess the uniformity of current strength across the harbour on the flood because of possible lag dye deposits, but indications are that a strong, oblique current exists within the first 2-3 km of the harbour entrance flowing from north to south. This is confirmed from current data at minor sites and from surface float tracking studies completed by the Lyttelton Harbour Board in 1950 and shown in Figure 4.16.

The flood pattern adds further credence to current velocity profiles at sites C_2 and C_3 (Fig. 4.12A-C) and to the possibility of partially mixed estuarine-type profiles as a result of density factors. Examination of Figure 4.17, in which vertical profiles of dye concentrations have been drawn, shows that all sites sampled on the flood tide, 25-36 (37-40 are not profiled as they were only sampled at 0.2 depth), with the exception of site 30 have high dye concentrations at mid and bottom depths. This is especially so on the southern side and points towards an earlier and/or stronger flood current in lower depths in this locality than on the surface. Alternatively it may reflect varying degrees of mixing when one considers the other dye profiles as well, although salinity data indicate the water column is well mixed towards the lower harbour and harbour entrance. If in fact layered flow is present in these regions as well as the narrow 'transition' zone, then harbour circulation can presumably be regarded as having a vertical as well as a horizontal component.

4.3 CIRCULATION PATTERNS

A valid prediction of circulation patterns is

Figure 4.17 Dye concentration profiles at a number of sample sites. The profiles give an indication of the degree of vertical mixing throughout the water column.


0·8
0·6
Z/Z0 0·4
0·2
0
40 50 60 70 80
Dye Concentration
(ul / l x10^-6)
1
2
3
19
20
21
5
6
22
23
24
7
8
9
25
26
27
10
11
12
29
30
31
13
14
16
32
33
36

attainable by collating the various disperson and current data. Initial inspection of current directions and velocities discussed earlier indicates a dominantly clockwise circulation with the main flood stream moving up the south side of the harbour and the main ebb stream down the north side. For some of the time this pattern prevails and is relatively simple, but the remaining period of each tidal cycle involves a complex circulation.

Variations in tidal flow in Lyttelton Harbour have been commented on by Brodie (1955), Bushell and Teear (1975), Garner and Ridgway (1955), and Heath (1975). Beyond these observations no further investigations have been carried out into circulation. Besides the broad-scale clockwise pattern there are locally induced eddies within the harbour causing rotatory currents, the most obvious of which develops from the tip of the breakwater and is recorded in the form of continuous and lengthened flood currents at tidal stations 7 and 8 respectively.

Turbulence resulting from flow around the breakwater can be demonstrated mathematically using the 'wake parameter' of Wolanski, Imberger, and Heron (1984):

$$P = \frac{UH^2}{K_z D} \qquad (4.1)$$

where: U = the current velocity (ms^{-1})

H = depth (m)

K_z = the vertical eddy diffusion coefficient (m^2s^{-1})

D = the length of the breakwater (m)

K_z may be estimated as 0.067 HU_* (Fischer <u>et al</u>. 1979) with U_* given by $C_D^{\frac{1}{2}}\, U_{100}$ where C_D is the bottom drag coefficient, U_* is the shear velocity, and U_{100} is the current velocity at 1 m above the bed. Assuming $C_D \simeq 3 \times 10^{-3}$ (Sternberg, 1972) and $U_{100} = 0.22$ ms^{-1}, we arrive at a value for K_z of around 0.01 m^2s^{-1}. This gives a value of P>>1 for both flood and ebb tides on either side of the breakwater, leading to unstable eddies forming downstream of the breakwater (Wolanski, Australian Institute of Marine Science; *pers. comm.* 1984). Records of the eddy at tidal station 8 indicate it to be at least four times the length of the breakwater downstream, and boat movements at the wharves confirm its presence at a similar magnitude upharbour on flood tides.

The effect of currents off the tip of the breakwater was recorded weakly at station 3 which has a slightly rotatory current in the change from ebb to flood tides. Remaining stations recorded largely bidirectional currents. This was not surprising as, with the exception of 1 and 2, stations were located around the perimeter and in particular, the oblique flood flow through the entrance was not recorded. Sediment transport and distribution patterns, erosional and depositional zones, and areas of fluid mud implied a more complex hydraulic system however. Heath (1975; p.456) concluded that flow through the entrance was not uniform, with "...considerable difference in the direction of flow at different parts of the entrance at any one time". The concept was not developed further.

Investigations into circulation were therefore continued in this study, although a major deficiency in data was a lack of simultaneous current station recordings. In order to overcome this all records were correlated with a single reference point, the inner harbour tide gauge. Changes in current direction from ebb to flood and *vice versa* at each station were plotted against the rise and fall of the tide on

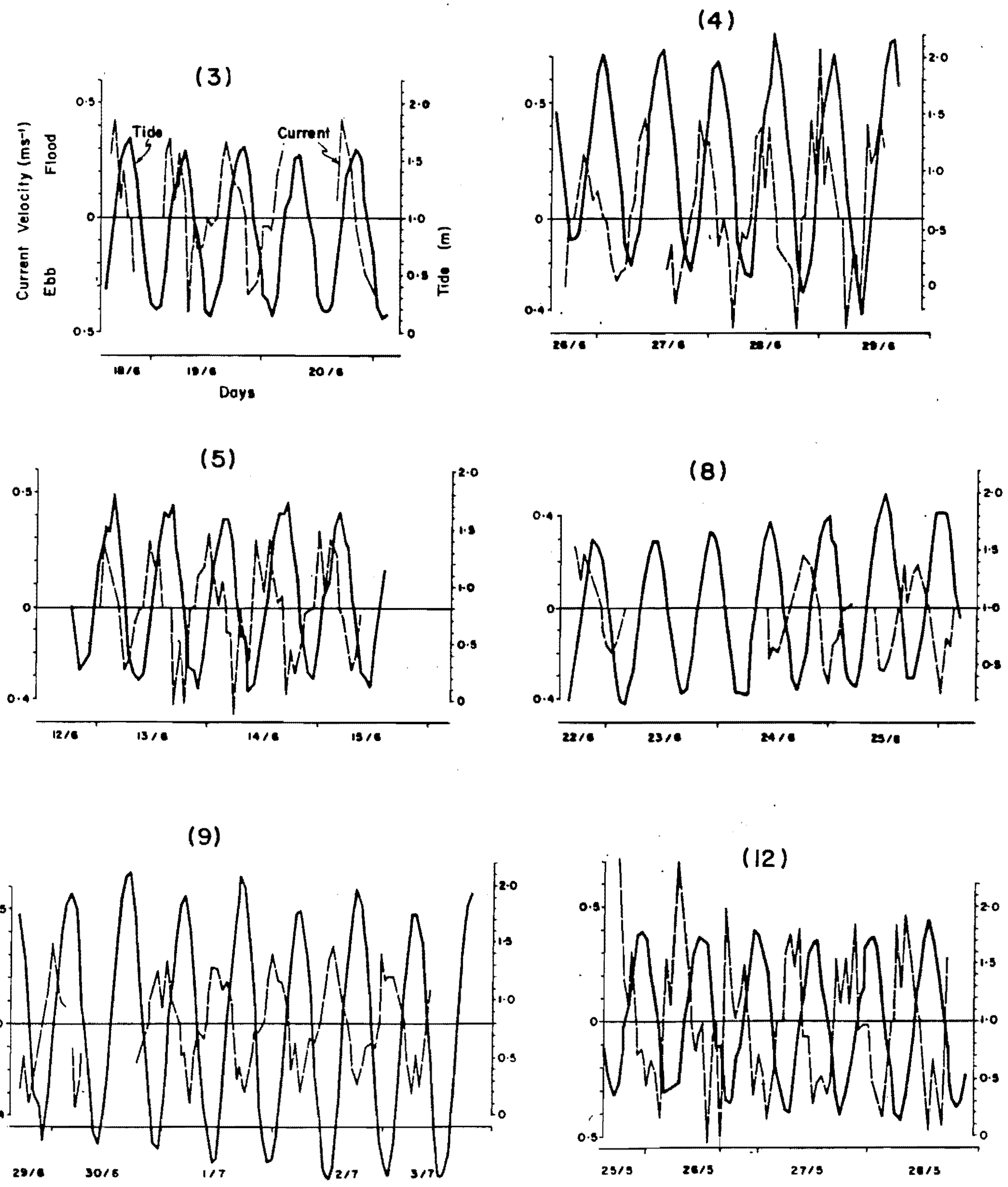


Figure 4.18 Current flow data from current stations plotted against simultaneous water level curves from the tide gauge. The curves were used to examine the times of flow direction change at current stations with respect to high and low water at the tide gauge.

the gauge for the same time period. These graphs are shown in Figure 4.18. As far as possible, averaged comparisons of changes in the tide with changes in flow direction at each station produced a measure of simultaneity or synchronisation of all the records. Table 4.4 lists comparisons of time deviations in change of flow with change of tide at the gauge for a number of tidal stations. Data from stations 1, 2, 10 and 11 were of insufficient duration or quality to include, and 7 was known to be a continuous flood current.

From the average value column in Table 4.4, circulation patterns for the periods 1.3 hrs before low water to low water, and 2 hrs before high water to high water, have been drawn in Figures 4.19A and B. The absence of current data from the centre of the harbour means the structure of the circulation or gyre drawn is purely deductive with neither the precise location of shear forces in the centre nor the velocity gradient across the shear able to be established. Given the locations of the available current data however, the positions of the rotatory currents at either end of the gyre are logical. Harbour widths are considered too narrow for the Coriolis force to induce such marked circulation (discussed by Dyer, 1979; Glen, 1979; McDowell and O'Connor, 1977; and others), and it is proposed here that topography is the main influence generating rotatory currents. On ebb tides circulation results initially from formation of an eddy as currents flow through the narrow constriction past the port, and around into Gollans Bay. Using equation (4.1) again, with $U = 0.23\ ms^{-1}$ (average ebb velocities for northern stations 8,9 and 10); $K_z = 8.018 \times 10^{-3} m^2 s^{-1}$; $H = 9.5$ m (MSL); and $D = 1000$ m (being the perpendicular distance between the

Table 4.4 Times of current direction change at designated stations with respect to observed times of high and low water on the inner harbour tide gauge. Positive values are times after the gauge; negative values before.

Station No.	Tide Changing To:	Time Deviation from Tide Gauge (Hrs) Average	Max.	Min.
3	Ebb	+0.2	+0.4	0
	Flood	+1.2	+1.6	+0.5
4	Ebb	+0.3	+1.0	0
	Flood	0	+0.3	0
5	Ebb	+0.2	+1.5	0
	Flood	+0.1	+/-1.0	0
6*	Ebb	+0.1	+0.4	0
	Flood	0	-0.9	0
8	Ebb	-1.0	-2.5	-0.5
	Flood	-1.7	-2.2	-1.5
9	Ebb	-2.0	-2.7	-1.3
	Flood	-1.7	-3.0	0
12	Ebb	-2.0	-3.5	-1.0
	Flood	-1.4	-2.5	-0.3

* Lyttelton Harbour Board data collected from water level surveys at the Camp Bay jetty in 1930 and 1933.

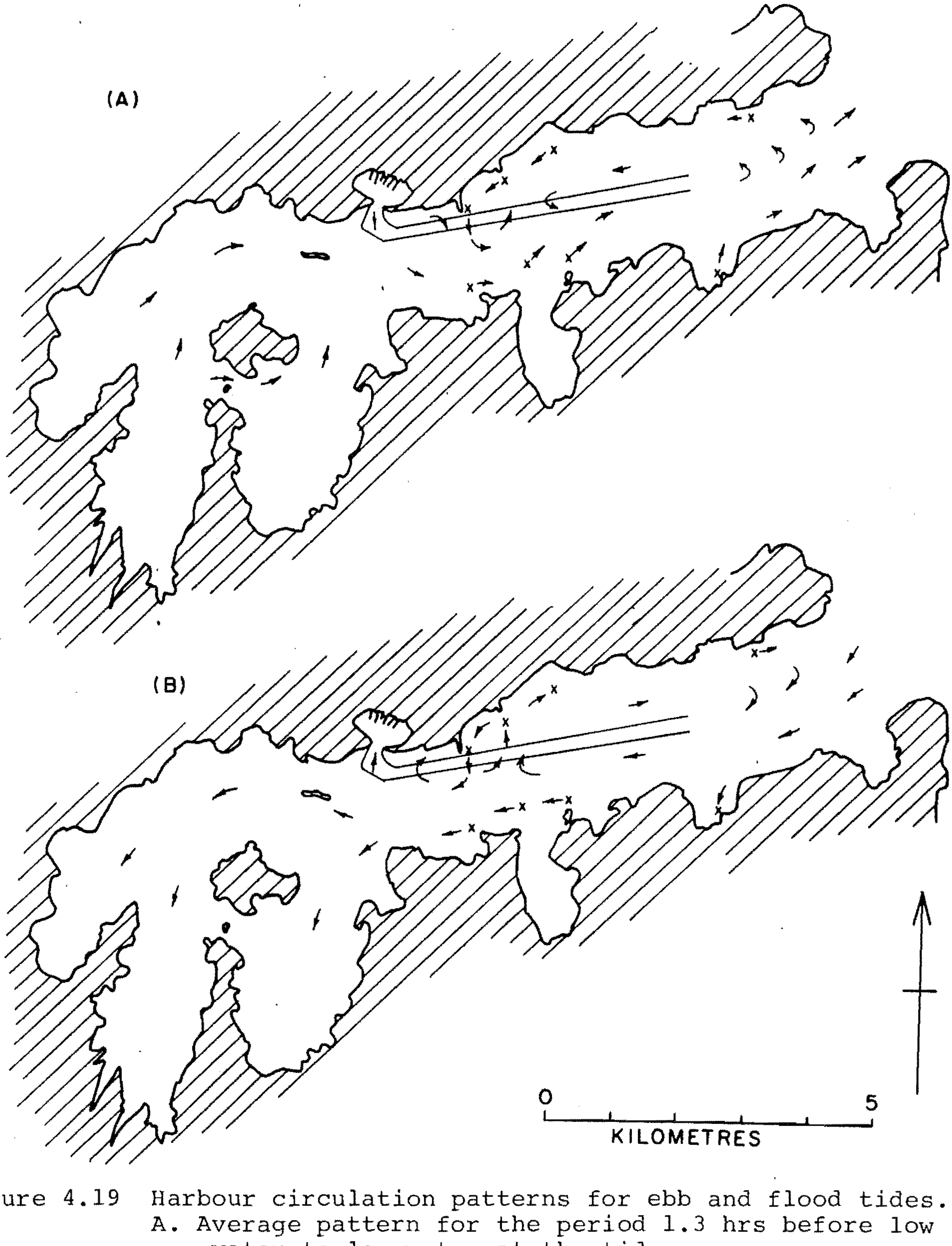


Figure 4.19 Harbour circulation patterns for ebb and flood tides.
A. Average pattern for the period 1.3 hrs before low water to low water at the tide gauge.
B. Average pattern for the period 2.0 hrs before high water to high water at the tide gauge.
Crosses are current stations where data was obtained at z = 1.5 m.

wharf frontage west of the breakwater and the shore in Gollans Bay (Fig. 4.20A)); a value for P of 2.589 is obtained. Wolanski et al. (1984) state:

> For P ≃ 1...a stable wake is present. As P further increases, the vorticity flux at the point of separation cannot be entirely negated in the eddy, and instabilities can be expected to develop further downstream...For P>>1, bottom frictional effects are negligible and the downstream flow can be expected to be similar to the flow around obstacles at large values of the Reynolds number in the laboratory....

Thus as the tide ebbs through the narrowest harbour section and flows into Gollans Bay a wake develops, tending to become unstable, with the separation point in the region between Diamond Harbour and the wharves opposite at the port. The presence and location of the breakwater are considered to be incidental to the system although it is likely to exacerbate the situation by inducing its own eddy.

From average values in Table 4.4 circulation can be seen to develop from an initial eddy around Gollans Bay into a large gyre the length of the lower harbour (see Figures 4.20B and C). An opposing gyre develops on the flood tide in similar fashion (see Figures 4.20F and G), presumably resulting from the oblique angle of flood currents to the harbour mouth which induces rotatory currents around Godley Head. It can be seen that the gyre develops towards the end of the tides, possibly caused by the exceedence of a critical tidal velocity (Ferentinos and Collins, 1979) although this is not readily ascertained from available data. Certainly though, when the maximum and minimum columns in Table 4.4 are considered, the duration of the gyre is likely to vary considerably over a large number of tidal cycles.

Development of the ebb gyre was examined further by

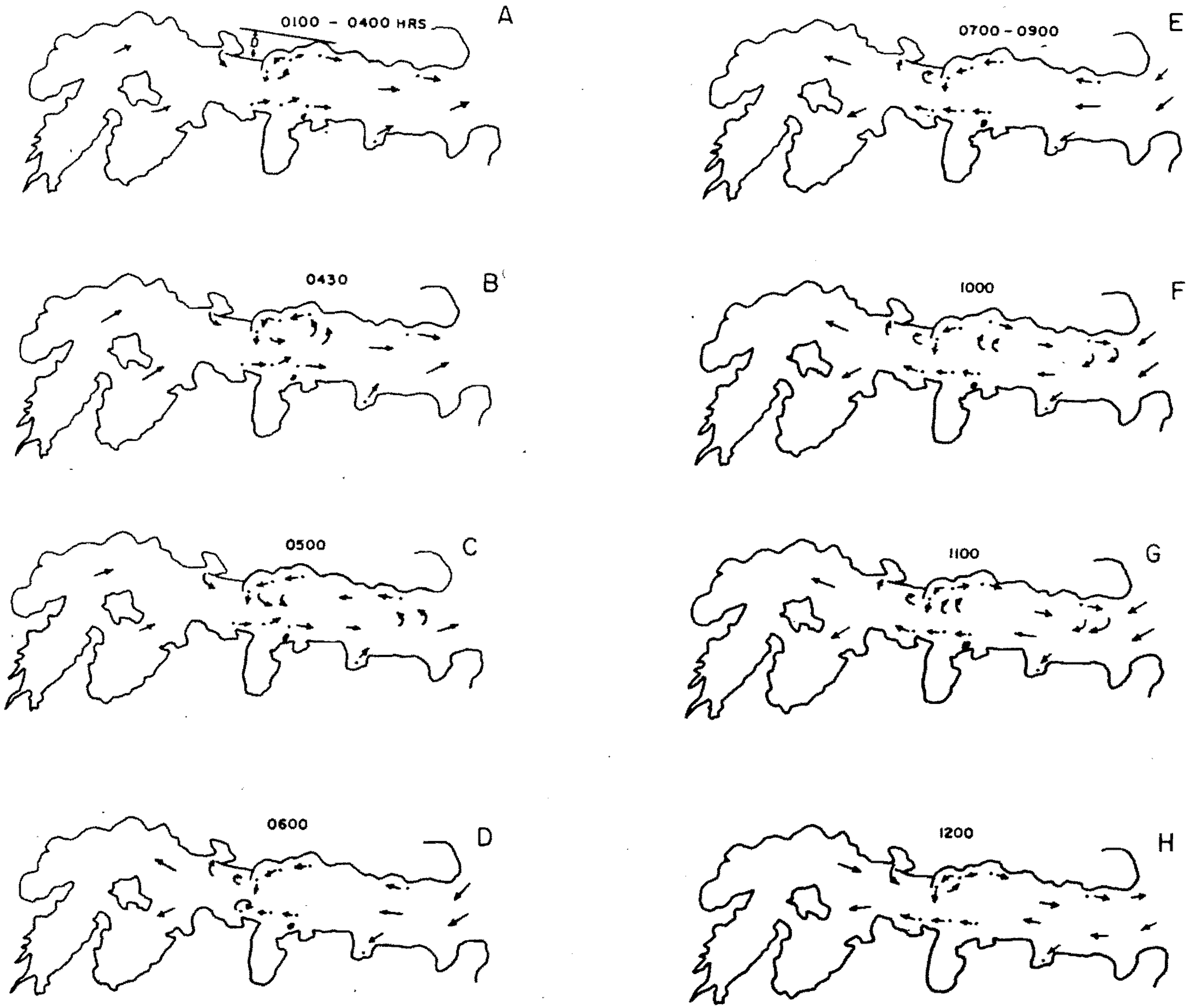


Figure 4.20 Development of the harbour circulation pattern for average flow conditions over a tidal cycle.

surveying changes in water levels at two locations simultaneously on 5 April 1984, and comparing these to the inner harbour tide gauge. Figure 4.21 shows the results of the survey, at Gollans Bay and Breeze Bay, in which the change from ebb to flood occurred an hour earlier at Gollans Bay than at Breeze Bay or the gauge. Simultaneous tide changes at Breeze Bay and the gauge suggests that the gyre did not develop fully on this occasion, which concurs with the notion that variations in the duration of the circulation pattern will generate proportional variations in the size, or degree of development, of the gyre. At times it may fail to develop; presumably the case when Garner and Ridgway (1955) measured tide fluctuations simultaneously at five locations and found no variations. It is worth noting from Figure 4.21 that the rate of change of the tide (current acceleration or deceleration) varies from site to site. Thus although the change from ebb to flood was simultaneous at Breeze Bay and the gauge, the tide was ebbing at considerably greater velocities in the inner harbour than at Breeze Bay two hours prior to low water. This in itself may cause the gyre to develop fully along the length of the lower harbour and supports the critical (or relative) velocity concept.

Two assumptions have been made in presenting these circulation diagrams. Firstly that averaged data (Table 4.4) can be applied to all tidal stations simultaneously and be collectively representative of any particular tidal cycle; and secondly that during the one to two hour periods around high and low water there is actually sufficient current flowing to sustain the predicted circulation pattern. The latter may be questioned with regard to circulation at the

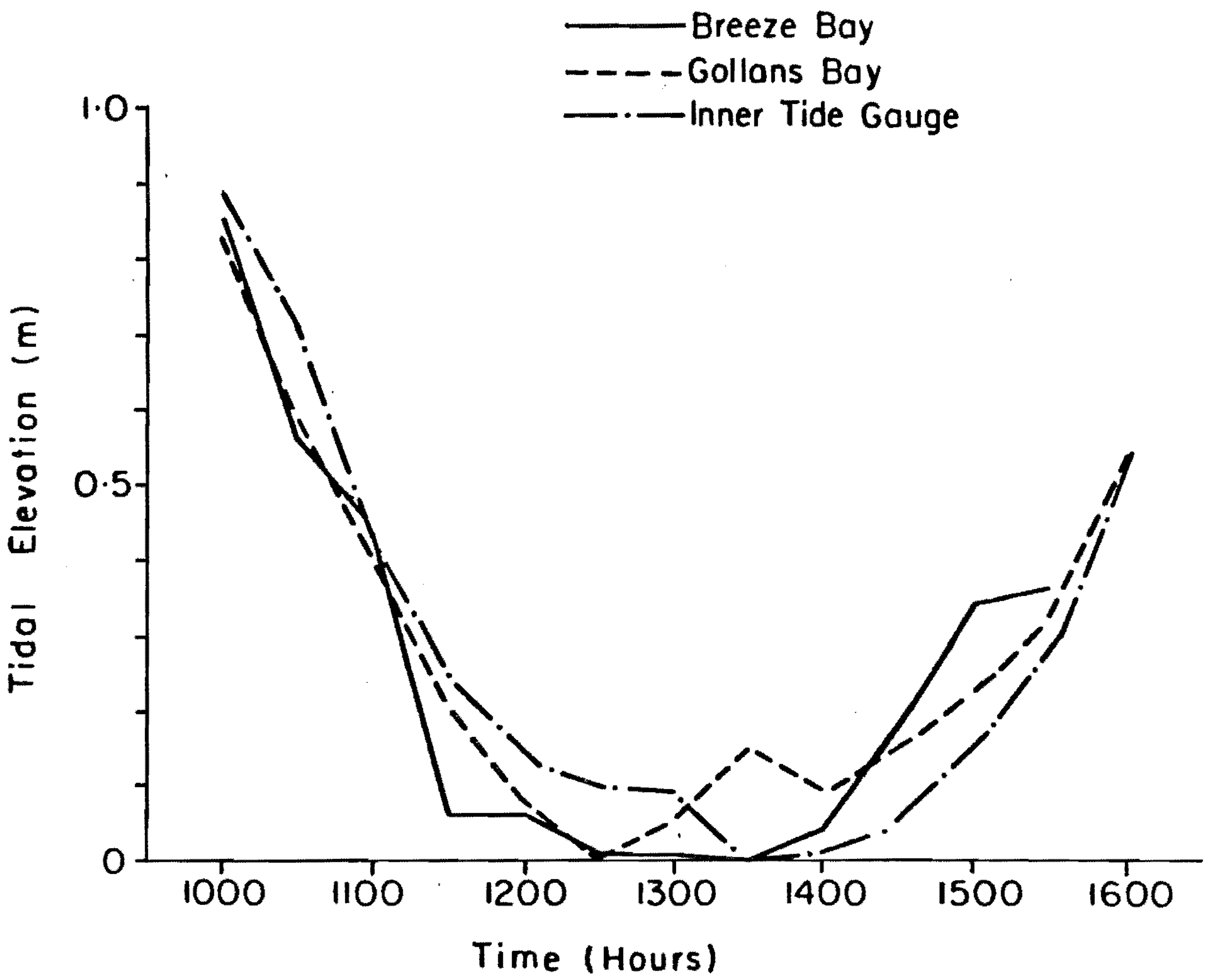


Figure 4.21 Surveyed water level changes at Gollans Bay and Breeze Bay over half a tidal cycle (5.4.84). Low water at each site has been adopted as the zero datum.

end of the flood tide (Fig. 4.20H) where tide changes exhibit only a few minutes variation (Table 4.4). However, it was earlier demonstrated that slack water occurs as much in the middle of a tide as at the end. Figure 4.22 presents vertical aerial photographs obtained on 26 September 1973 which depict clearly the presence of an eddy around the channel off Battery Point near predicted low water. Possible shear zones can also be seen along the centre of the harbour. Such shear forces and eddies associated with such a circulation pattern must be of considerable consequence to harbour sedimentation and hydrodynamics.

4.4 SUMMARY

It has been established from two salinity surveys that Lyttelton Harbour is not an estuary within the definition supplied by Cameron and Pritchard (1963). Minimum salinity levels established near the low water mark were 30.9‰ and the overall longitudinal gradient was only 3‰. The lack of fresh water input and the negligible gradient were the primary factors in classifying Lyttelton as a non-estuarine environment.

Salinity patterns did, however, demonstrate the important division of the harbour into three hydraulic compartments; the upper harbour; the lower harbour; and the narrow 'neck' opposite the port separating the other two regions. These regions are divisible in terms of mixing processes depicted in vertical salinity profiles. The upper and lower harbours are both well mixed although a degree of stratification is evident at the landward extreme of the surveyed profile. The narrow centre region is less well mixed, and more importantly it contains a high salinity zone which forms a seaward limit to

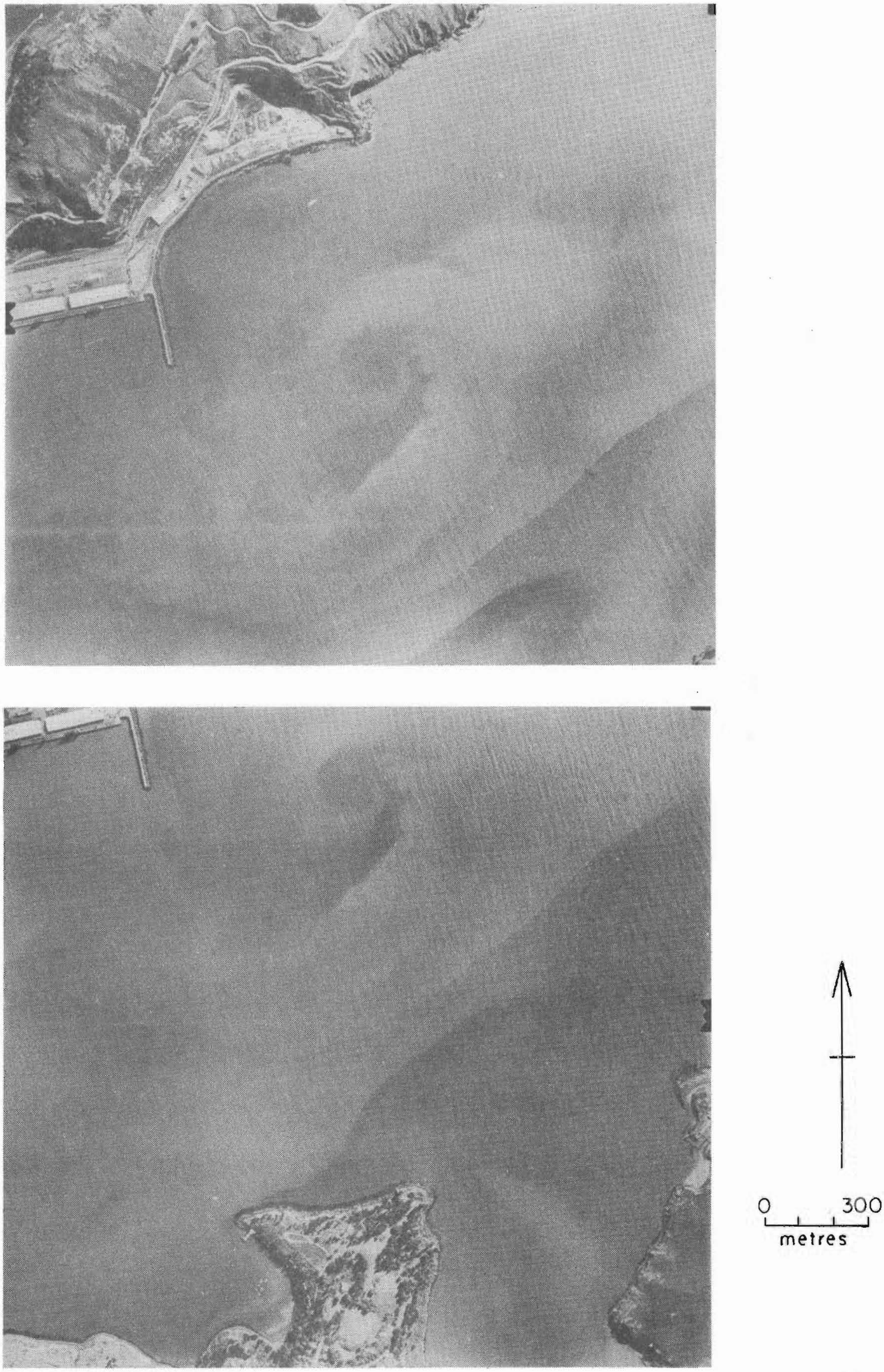


Figure 4.22 Aerial photographs showing the ebb tide eddy and the possible development of shear lines between the breakwater and the entrance to Purau Bay. Reproduced with the permission of the Department of Lands and Survey (SN 2634 0/15 and 0/16; 1973).

the upper harbour salinity structure and a transition between the upper and lower harbours.

Vertical salinity variations are generally in the order of 0.2-0.3^{o}/oo, with a maximum variation of 0.5^{o}/oo in the poorly mixed zone. While some degree of vertical density structure therefore exists, currents resulting from it are likely to be negligible in comparison with tidal currents. It is concluded that circulation within the harbour is tidally dominated and may be regarded as two-dimensional in a horizontal plane.

Current data and dye tracing have demonstrated the presence of layered flow on both ebb and flood tides, particularly in the narrow centre region, and along the southern side on a flood tide. Ebb currents flow obliquely, to the north in the upper harbour and east of the breakwater as far as Purau Bay. East of Purau Bay flow is predominantly parallel to the longitudinal axis. In the narrow, transition zone flow is slightly oblique across the channel on the surface, and along the channel on the bottom. In mid-depths the flow is forced towards the south opposite the port, then rotates back towards the north once past the breakwater. Bottom flow tends towards the north once past the breakwater but the obliqueness is less marked at this depth. The tide floods at an oblique angle to the harbour axis from north to south through the harbour entrance. This occurs only within the first 2-3 km after which flood currents also parallel the longitudinal axis.

Circulation was examined by correlating current direction at tidal stations with the tide curve on the inner harbour tide gauge. This established the presence of a large clockwise gyre on the flood tide (at the gauge) and a similar anticlockwise gyre on the ebb tide (at the gauge). Circulation is induced by topographical influences on tidal currents and the oblique angle of tides to the harbour. Rotatory currents are inferred at the harbour entrance and near the breakwater, with no evidence found for the existence of a circulation system in the upper harbour. Thus the hydraulics can again be divided into upper and lower harbours on the basis of circulation, with the transition zone located in the narrow, centre region. Flow separation on the ebb tide, which results in the lower harbour gyre, is inferred to occur within the narrow region.

Duration of the gyre and rotatory currents is variable for any given tidal cycle. It is concluded that this is a function of tidal variability; the length of ebb and flood tides recorded at the tide gauge varying unsystematically between five and eight hours approximately. Tidal variability is itself significantly influenced by two parameters external to the harbour and to normal tidal constituents. These are weather patterns along the east coast of the South Island, reflected in pressure differentials between Dunedin and Christchurch cities, and a continental edge wave oscillation which occurs in the harbour with a 2.5 - 3.5 hr period. Spectral analysis of the tidal wave has demonstrated that while the main tidal component is the lunar M_2 constituent, weather forcing and edge wave oscillations exert an influence on the tides comparable to that of other significant constituents such as the M_f (spring and neap) constituent.

While questions raised in chapter one regarding the stability of the harbour can not yet be answered, this chapter has identified the main hydraulic characteristics of the harbour which are likely to have a controlling influence on stability. The influence of a hard, rock wall geometry on the circulation patterns within the harbour have been clearly demonstrated. It can be concluded that the hydrodynamics of Lyttelton Harbour are complex, strongly influenced by factors external to the harbour, and quite atypical of 'normal' estuarine and inlet hydrodynamics. The implications of this for sedimentation are discussed in the following chapter. Also in the following chapter, a further hydraulic parameter, the wave environment, is discussed and the interaction of waves with tidal currents and sediments is examined.

FIVE

EFFECTS OF WAVES AND TIDAL CURRENTS ON HARBOUR SEDIMENTATION

Coastal inlets, their sedimentation and cross-sectional form are influenced and to a degree controlled by three types of induced currents; tidal, wave, and density. The comparative influence of these currents depends on the type of inlet being examined, and superimposed on these general hydraulic components will be local effects such as surges, resonance, wind induced currents, and wave drift currents past the entrance. In stratified and partially mixed estuaries density currents are the dominant hydraulic process, while for most inlets of any form wave effects occur only within the mouth and initial entrance. Tidal currents are normally the dominant hydraulic parameter in non-estuarine inlets and probably in well mixed estuaries as well.

Controls exerted by the hydraulic parameters of an inlet on sedimentation, stability, and circulation will be affected by other variables such as sediment supply, freshwater inflow, and inlet structure or topography. Lyttelton Harbour is neither an estuary (section 4.1), and is therefore not affected by freshwater inflow and density currents; nor a "littoral drift tidal inlet" with two or three 'mobile' boundaries. Rather it is a tidal inlet with structural controls; one mobile boundary only, and the hydraulics and circulation confined within two rigid rock boundaries. This form of inlet is rarely discussed, if at all, in text reviews of estuaries and inlets and yet its sedimentation patterns (chapter three) are complex, distinctive, and clearly determined by hydrodynamics. This chapter examines a further hydraulic variable, wave activity, frequently of little influence in inlet dynamics, prior to discussing the implications of Lyttelton Harbour hydrodynamics for sedimentation.

5.1 WAVE ANALYSIS

5.1.1 Wave Spectrum

Wave records were obtained by the Lyttelton Harbour Board within the harbour off Battery Point (Fig. 5.5) between 1955 and 1959. At the time records were collected the breakwater had not been constructed, so that there were no problems of reflection near the instrument. The recording device consisted of a Piezo electric pressure unit laid on the sea bed in 9.5 m of water (MSL) and connected to shore power supply and recording units by cable. Recording was either continuous or for 17 minute intervals every two hours and the instrument was capable of accurately gathering data on waves over 0.3 m in amplitude. Long period, low amplitude waves and seiche effects were not recorded.

Three years of data from December 1955 to December 1958 have been analysed here. Due to instrument calibration and frequent periods of low amplitude waves, not all records were satisfactory for digitizing and two methods had to be adopted for analysis. Those data with low amplitude waves were compared visually, as a 17 minute recording interval, with selected "standards" taken from the records which were enlarged and digitized. Figure 5.1 depicts examples of

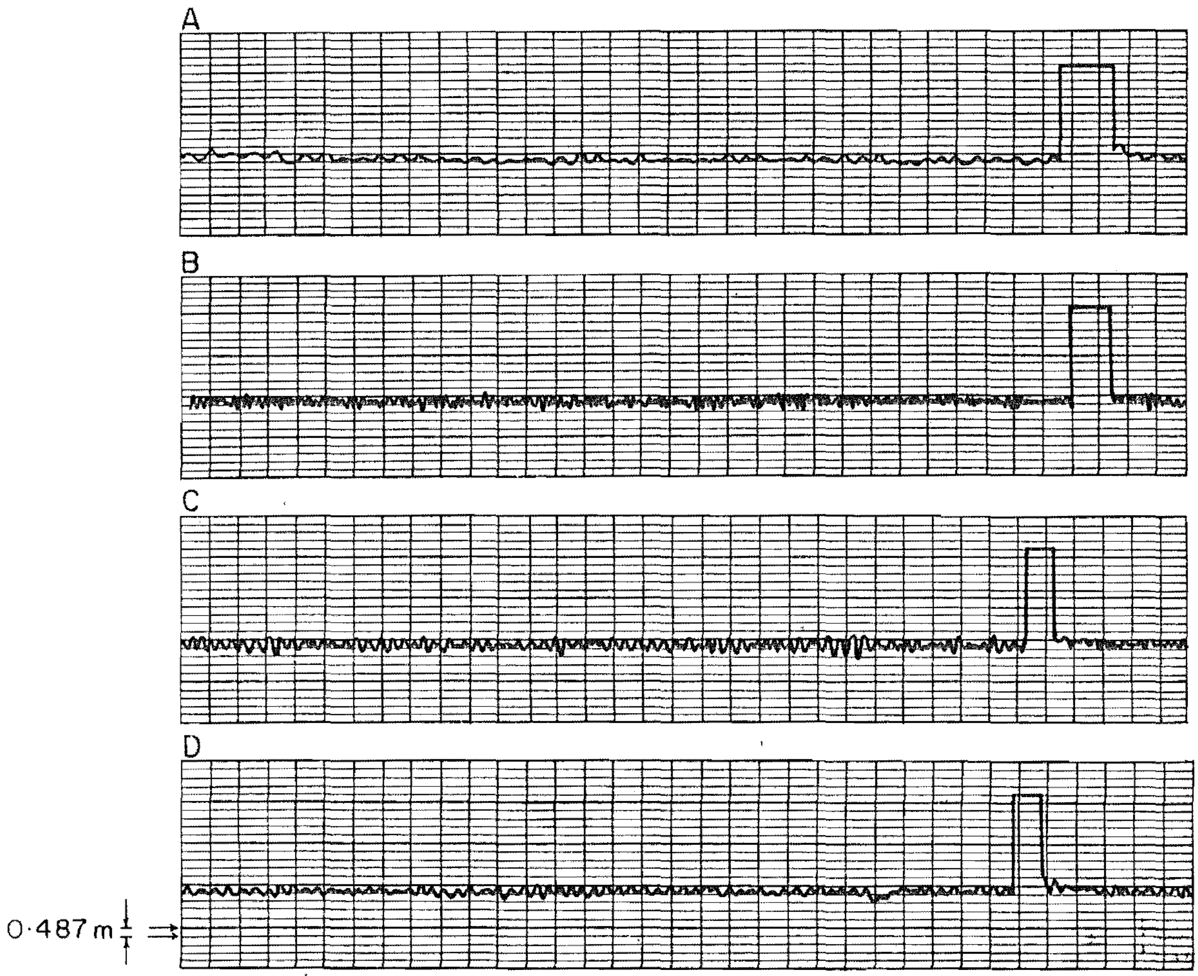


Figure 5.1 Examples of wave chart categories used as standards for wave analysis. These records were unsatisfactory for digitizing.
A. Long period (20s) low amplitude (≤0.25 m) waves
B. Short period (7s) low amplitude (0.5-1.0 m) waves
C. Middle period (11s) medium amplitude (0.5-1.5 m) waves
D. Middle period (12s) low amplitude (0.5 m) waves.

these standards. This allowed rapid and effective analysis of records which were generally too small to be digitized. Remaining data were digitized, on a Wang 2200-S computer in the Geography Department, which entailed placing a digitizer cursor on every turning point on the record (i.e. every peak and trough was digitized). A number of parameters were determined from this analysis including $H^{\frac{1}{3}}$ and $T^{\frac{1}{3}}$, significant wave amplitude and period respectively. These were the primary parameters utilized in subsequent wave variable calculations. Period (T) was calculated directly from the charts. However, as the instrument was a pressure type, sea bed recorder, calculation of wave amplitude (H) had to account for the hydrostatic effects of water depth. Hastie (1983) examined the theory for pressure type wave recorders; and the following formula was adapted from Hastie for the determination of wave amplitude:

$$H = \cosh (2\pi d/L)a. \tag{5.1}$$

where: H = surface wave height (m)

d = water depth (m)

L = wavelength (m)

a = calibration of pen movement to chart intervals and recorded value (m)

Data extraction involved several steps. Firstly, the amplitude and period of the recorded waves were digitized. This required establishing a 'zero' line with the digitizer, through the records for each 17 minute recording interval examined. To digitize a 'wave' the digitizer cursor had to locate consecutive peaks and troughs on either side of the 'zero' line. The level of accuracy of the cursor meant that this was not possible for the smaller records, where wave peaks and troughs could not be distinguished from the zero line, which was why not all the records could be digitized. Digitized data were recorded on disk, with identification, for 17 minute recording intervals. This information was then read back into the computer, again in 17 minute intervals, and real wave heights were calculated from equation (5.1). Significant wave height and period for each recording interval were then calculated. These could then be averaged if wave statistics were required for a longer period, such as a complete storm event.

Since "standards" were used and many data were categorized in 17 minute recording periods, rather than being digitized wave by wave, summary statistics represented recording periods also. $H^{\frac{1}{3}}$ and $T^{\frac{1}{3}}$ parameters for digitized data were therefore combined with non-digitized data to obtain eight main categories of recording periods listed in Table 5.1. Estimation of the number of waves for each significant wave period was based on the average number of waves per recording interval from those data which were digitized. This calculation was necessary to obtain the total number of waves for the three years in order that percent occurrence of waves in each category could be calculated. Figure 5.2 portrays these figures diagrammatically showing the wave spectrum for Lyttelton Harbour.

Twenty second waves are the most frequently occurring in the spectrum but are of very low amplitude. Combined with still water, 22% of the time, low energy conditions prevail within the harbour for 53% of the time. Relatively low amplitude, 12 second waves occur 24% of the time, while storm waves (steepness $\geq$0.013) are present in the harbour only

Table 5.1 Main wave recording categories in terms of significant height and period.

$T_{\frac{1}{3}}$ (secs)	No.of Periods	$H_{\frac{1}{3}}$ (m)	Approx.No. Waves/Period	No.of Waves	Percent Occurrence
7	616	1.10	104	64,064	8.68
9	265	1.60	90	23,850	3.23
11	722	1.50	79	57,038	7.73
11	195	2.40	79	15,405	2.09
12	2,413	0.65	74	178,562	24.20
18	181	0.60	56	10,136	1.37
20	4,533	0.25	50	226,650	30.72
Still Water	2,515				21.98

14% of the time. A maximum amplitude of 2.4 m (Table 5.1) is by no means indicative of the maximum wave height found in the harbour, but is merely the maximum significant wave height for the categories representative of the wave spectrum. In fact wave heights of 4.3 m were recorded, but these were most infrequent and were associated with a single storm event.

Wallingford Hydraulics Research Station (Report No.EX862, 1979) investigated wave records from the port wharf frontage using spectral analysis which showed strong peaks for long period waves, T>50 seconds, and swell with 10s<T<20s. The report indicates that the amount of long wave energy is larger than the swell energy. However, it should be noted that only the highest energy wave conditions were examined (E.C. Bowers, WHRS, *pers comm*, 1983), representing only a small portion of the records. Furthermore, spectral analysis is subjective in its "window" selection for analysis of data. No evidence exists in the Battery Point data to suggest the presence of wave or swell periods greater than 20 to 25 seconds although it must be reiterated that pressure type recorders tend to damp out long period waves. The Wallingford report did locate considerable wave energy in the 10 to 20 second period range, consistent with data in Table 5.1 showing 11 and 12 second waves occurring 34% of the time. Hastie (1983) showed there is a 45% occurrence of 10 and 11 second wave periods along the Canterbury coast south of Lyttelton, but recorded no data at periods longer than 16 seconds.

5.1.2 Wave Effectiveness

Horizontal water currents are induced beneath waves by the motion of individual water particles. In deep water, in a

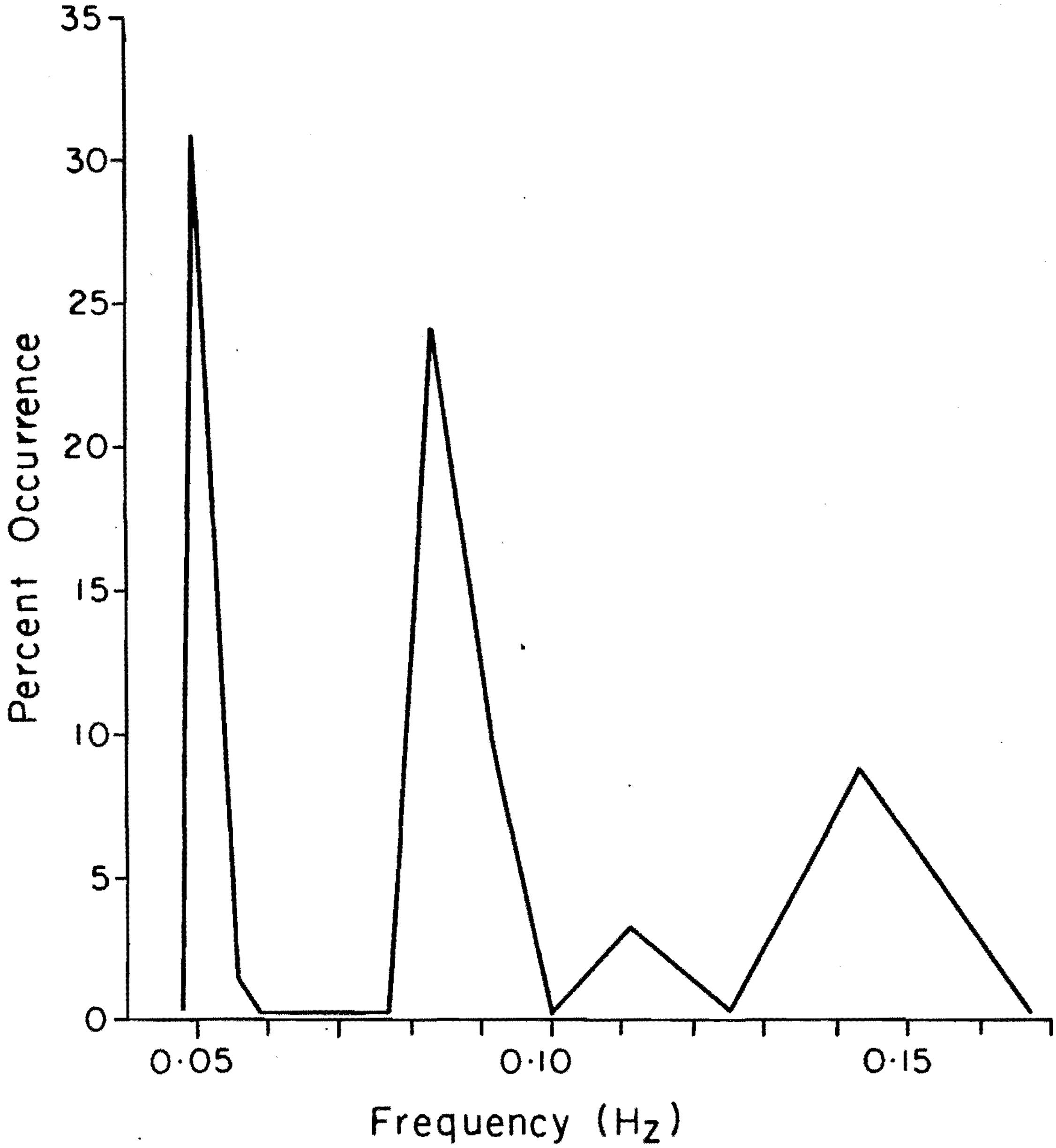


Figure 5.2 Wave spectrum. Data are from averaged recording interval categories.

sinusoidal wave profile (Airy wave), the orbits of water particles are closed circles. The orbits become ellipses in shallower water due to the effect of the sea bed reducing the vertical movement of water particles (Mason, 1951). Orbits in a Stokes' wave are not closed and lead to a slight net transport in the direction of wave propagation which produces wave drift currents. A more general expression for near-bed wave induced velocities is provided by Inman (1963a) from the maximum horizontal component of the orbital velocity of an Airy wave:

$$U_m = \pi d/T \qquad (5.2)$$

where U_m = maximum orbital velocity (ms^{-1})

d = horizontal diameter of the orbit (m)

T = wave period (s)

In shallow water the orbital diameter for an Airy wave is constant from the surface to the bottom and equation (5.2) simplifies to:

$$U_m = \tfrac{1}{2}\frac{H}{h}.C. \qquad (5.3)$$

where H = wave amplitude (m)

h = water depth (m)

C = wave phase velocity (ms^{-1})

In shallow water any vertical motion near the bed is lost and currents become a to-and-fro movement of water (Zenkovich, 1967; p.29). It is the direct tangential stress of this to-and-fro action coupled with the induced pressure field of the passing wave which effects the transport of sediment (Inman, 1963b; p.143).

However, variability in wave conditions (period, amplitude, wavelength) causes difficulties in assessing the relative effect on the bed and on sedimentation of components making up the wave spectrum. Particularly, the relative strength of the maximum near-bed velocity for a given wave form may be less important than its frequency of occurrences. To provide a means of relative assessment, McCave (1971; p.89) devised a "wave effectiveness" parameter defined as "...the product of theoretical instantaneous sediment transport rate times frequency [of occurrence]...". Following arguments by Inman (1963b) that the instantaneous sediment weight transport rate G produced by a wave is proportional to the available fluid power W, McCave demonstrated that G is proportional to Up^3, where Up is the significant peak particle speed at the bed.

> Expressing the percent of the time for which a given Up is exceeded as a fraction P,....Up^3 is proportional to the amount of work done per unit area of bed by waves of that particular P and Up. This may be viewed as a parameter expressing the effectiveness of the wave type on the bed.
> (McCave, 1971)

Because of the variance in the wave spectrum listed in Table 5.1, in period, amplitude, and frequency, the wave effectiveness parameter has been adopted here to examine the relative effects of the seven wave categories on different areas of the harbour bed. As a general rule reference to 'deep water' is made where depth (h) exceeds half the wavelength (L). However Inman (1963a) considers this too stringent for most practical purposes and proposes the criteria $h/L > \frac{1}{4}$ for deep water, $\frac{1}{4} > h/L > \frac{1}{20}$ for intermediate water, and $\frac{1}{20} > h/L$ for shallow water. These criteria are used for waves within Lyttelton Harbour. Equation (5.2) was used for the calculation of maximum orbital velocity (Up) in intermediate depths, and equation (5.3) in shallow water. Table 5.2 contains wave effectiveness values for the main wave categories within the harbour.

Table 5.2 Maximum wave effectiveness values for various wave forms at given depths (MSL)

$T^{\frac{1}{3}}$ (s)	Depth (m)	Up (ms^{-1})	P	Up^3P	Recorded $H^{\frac{1}{3}}$ (m)
	4	0.95	0.09	0.0772	
	6	0.66	0.09	0.0259	
	8	0.52	0.09	0.0127	
7	10	0.41	0.09	0.0062	1.10
	12	0.34	0.09	0.0035	
	14	0.28	0.09	0.0020	
	16	0.23	0.09	0.0011	
	4	1.28	0.03	0.0629	
	6	0.95	0.03	0.0257	
	8	0.83	0.03	0.0172	
9	10	0.68	0.03	0.0094	1.60
	12	0.58	0.03	0.0059	
	14	0.50	0.03	0.0038	
	16	0.44	0.03	0.0026	
	4	1.46	0.08	0.2490	
	6	1.08	0.08	0.1008	
	8	0.87	0.08	0.0527	
11	10	0.81	0.08	0.0425	1.50
	12	0.70	0.08	0.0274	
	14	0.61	0.08	0.0182	
	16	0.55	0.08	0.0133	
	4	2.34	0.02	0.2563	
	6	1.73	0.02	0.1036	
	8	1.39	0.02	0.0537	
11	10	1.30	0.02	0.0439	2.40
	12	1.11	0.02	0.0274	
	14	0.98	0.02	0.0188	
	16	0.87	0.02	0.0132	

	4	0.63	0.24	0.0600	
	6	0.47	0.24	0.0249	
	8	0.38	0.24	0.0132	
12	10	0.33	0.24	0.0086	0.65
	12	0.31	0.24	0.0072	
	14	0.27	0.24	0.0047	
	16	0.24	0.24	0.0033	
	4	0.59	0.01	0.0021	
	6	0.44	0.01	0.0009	
	8	0.35	0.01	0.0004	
18	10	0.30	0.01	0.0003	0.60
	12	0.26	0.01	0.0002	
	14	0.23	0.01	0.0001	
	16	0.21	0.01	0.0001	
	4	0.25	0.31	0.0048	
	6	0.19	0.31	0.0021	
	8	0.15	0.31	0.0011	
20	10	0.12	0.31	0.0005	0.25
	12	0.11	0.31	0.0004	
	14	0.10	0.31	0.0003	
	16	0.09	0.31	0.0002	

The calculated values demonstrate that 11 second wave categories, occurring 2% to 8% of the time, are at least three times and up to two orders of magnitude more effective than other wave categories at all depths. Seven to 11 second wave periods were all more effective than categories with periods greater than 12 seconds, due to greater wave amplitudes. Wave steepness was greater for these categories (0.008 - 0.014) than the >12s categories (0.0004 - 0.003), indicative of a correlation between higher wave amplitudes and stormier conditions.

Logically, for any given condition waves are more effective in shallower water (Figure 5.3B). However, from consideration of Figure 5.3A it is apparent this does not apply relatively throughout the wave spectrum. The two maximum values at each depth are those of 11 second waves with amplitudes of 1.5 and 2.4 m. Crossing of the lines in Figure 5.3A indicates that for much of the harbour 11 second waves are relatively more effective in performing sedimentary work at the bed in deeper water, than all other wave conditions are in shallower water. Thus an 11 second wave is more effective in 10 and 14 m of water than other wave categories are in 6 and 10 m respectively. Consideration of this fact and Figure 5.3B, showing the decline in effectiveness with depth, demonstrates the dominance of 11 second waves over other wave periods, in the control of near-bed processes in Lyttelton, despite the low percentage occurrence of 11 second waves.

Irrespective of this, if the maximum orbital velocities in Table 5.2 are compared with threshold erosional velocities for sand sized material (Fig. 5.4) it is clear that all wave conditions are capable of entraining the bulk of the coarser

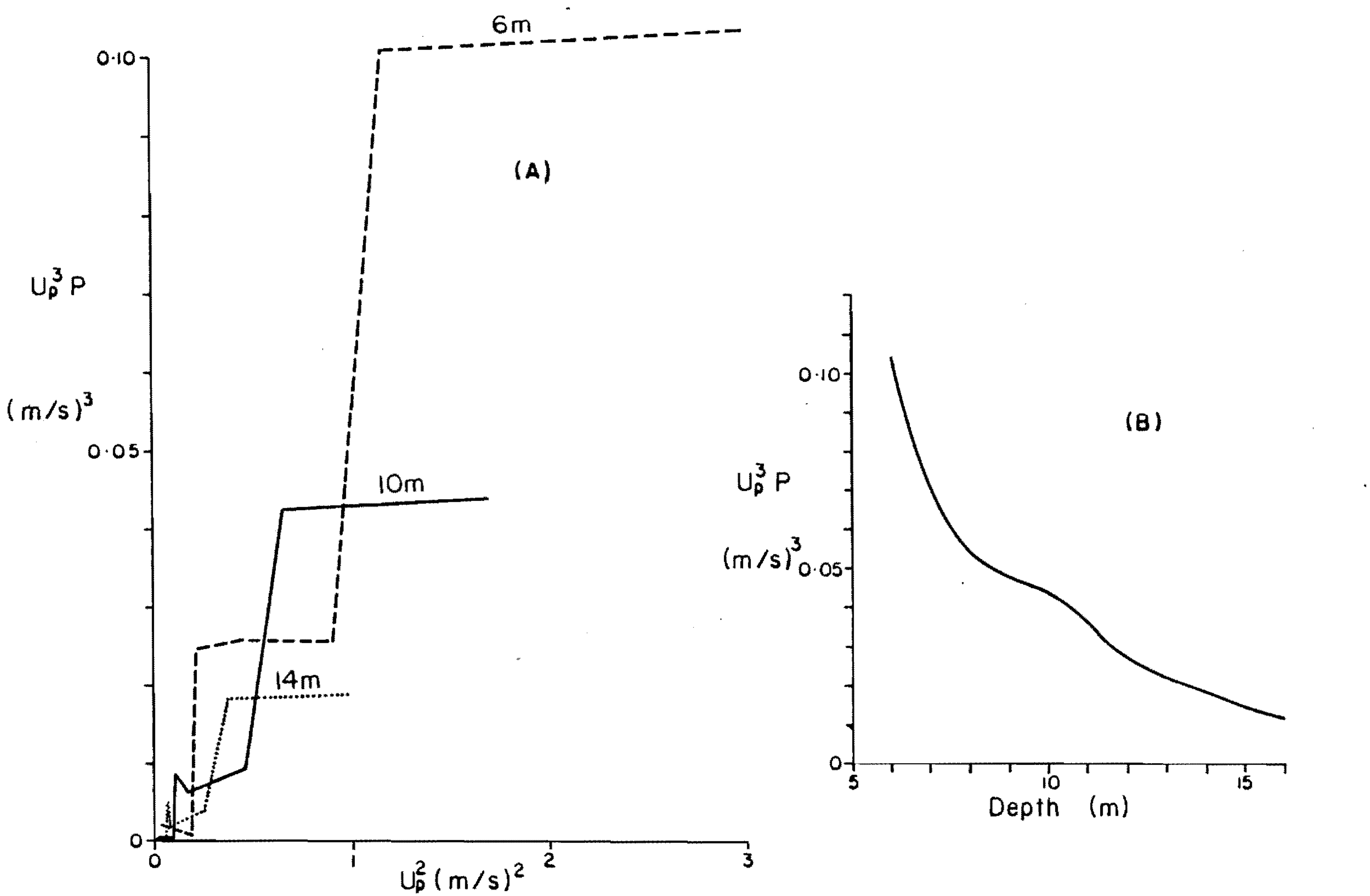


Figure 5.3 Graphs of the distribution of wave effectiveness with respect to harbour depths.
A. Distribution of wave effectiveness at the bed (Up^3P) vs Up^2 (proportional to shear stress) for several depths.
B. Maximum values of wave effectiveness (Up^3P) vs depth.

particles in the harbour. The exceptions to this are 20 second waves in depths greater than 7 m, or greater than 4 m for material coarser than 0.22 mm (fine sand); and 18 second waves in depths greater than 14 m for material coarser than fine sand. (A specific gravity of 2.70 used in these calculations was based on specific gravities of minerals (Lambe and Whitman, 1969) comprising sand grains in the harbour.) Threshold velocities in Figure 5.4 were calculated by computer using the method of Pickrill and Currie (1983).

Thus it can be stated that while 11 second storm waves are the most effective all wave categories are capable of entraining some sediments. In depths greater than 7 m waves will entrain sand sized material approximately 47% of the time, and for depths between 4 and 7 m sand finer than 0.22 mm will be entrained approximately 78% of the time. The spatial effects of these transport potentials depends largely on the spread or concentration of wave energy within the harbour.

5.1.3 Wave Refraction

The phase velocity of waves, from linear theory, depends upon both water depth (h) and wave length (L) in the ratio h/L. When h/L is large the phase velocity is a function of wave length only. When h/L is small phase velocity is a function of water depth and each part of a wave travels with a phase velocity dependent upon the water depth beneath it (Wiegel, 1964). Therefore a wave approaching the shore obliquely to depth contours will be travelling at different velocities along its length, causing the wave to refract toward shallower water so that the wave crests tend to parallel the depth contours (Inman, 1963a).

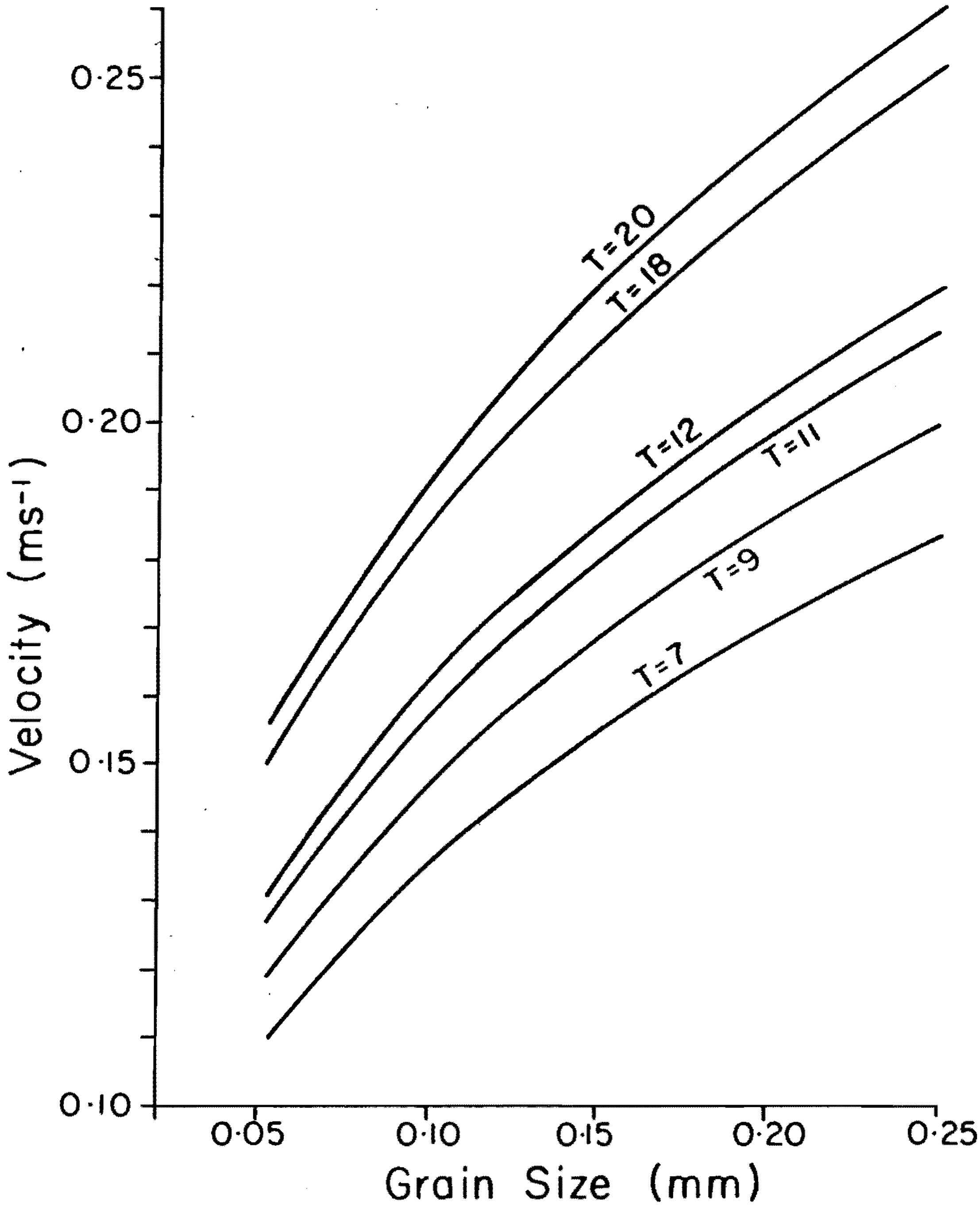


Figure 5.4 Threshold erosional velocities under waves for a number of wave periods. Velocities calculated after Pickrill and Currie (1983). Velocities are for a sediment grain density of 2.70 gcm^{-3}.

Refraction analysis was carried out on the University of Canterbury Burroughs B6900 mainframe computer, utilizing a programme by Wilson (1966). Three wave periods, 7, 11 and 20 seconds, were examined with all wave rays commencing at the 15 m contour (MLWS) outside the harbour entrance, approaching from an ENE direction. Ideally refraction diagrams should be initiated in 'deep water'. However, in this instance work by the Lyttelton Harbour Board using a grid commencing in deep water has shown that wave energy enters from the ENE (e.g. see Bushell and Teear, 1975), including waves from the south which are refracted around Banks Peninsula. Bathymetric data for this investigation were obtained from the 1976 Hydrographic chart NZ6321 and a 1981 Lyttelton Harbour Board sounding plan.

Figure 5.5 portrays refraction for the three wave periods. Spoil mounds, particularly at White Patch Point, are effective in inducing refraction while divergence of orthogonals occurs away from the channel. These effects are maximised for longer period waves. The net effects of bathymetry are to concentrate wave energy in areas between Camp Bay and Purau Bay, between Breeze Bay and Livingston Bay, and around Battery Point on the northern side. Limited energy occurs in Little Port Cooper, and in Diamond Harbour for shorter period waves. For all the wave periods examined, considerable energy occurs by convergence at the western side of the entrance to Camp Bay, and the entrance to Purau Bay. These two sites correspond to maximum scour relative rollability values for very fine sand (Fig. 3.12) and whole samples (Fig. 3.11) respectively. It is also interesting to observe that as the wave period decreases, orthogonals tend to refract more towards the southern side of the harbour. Referring back to threshold erosional velocities

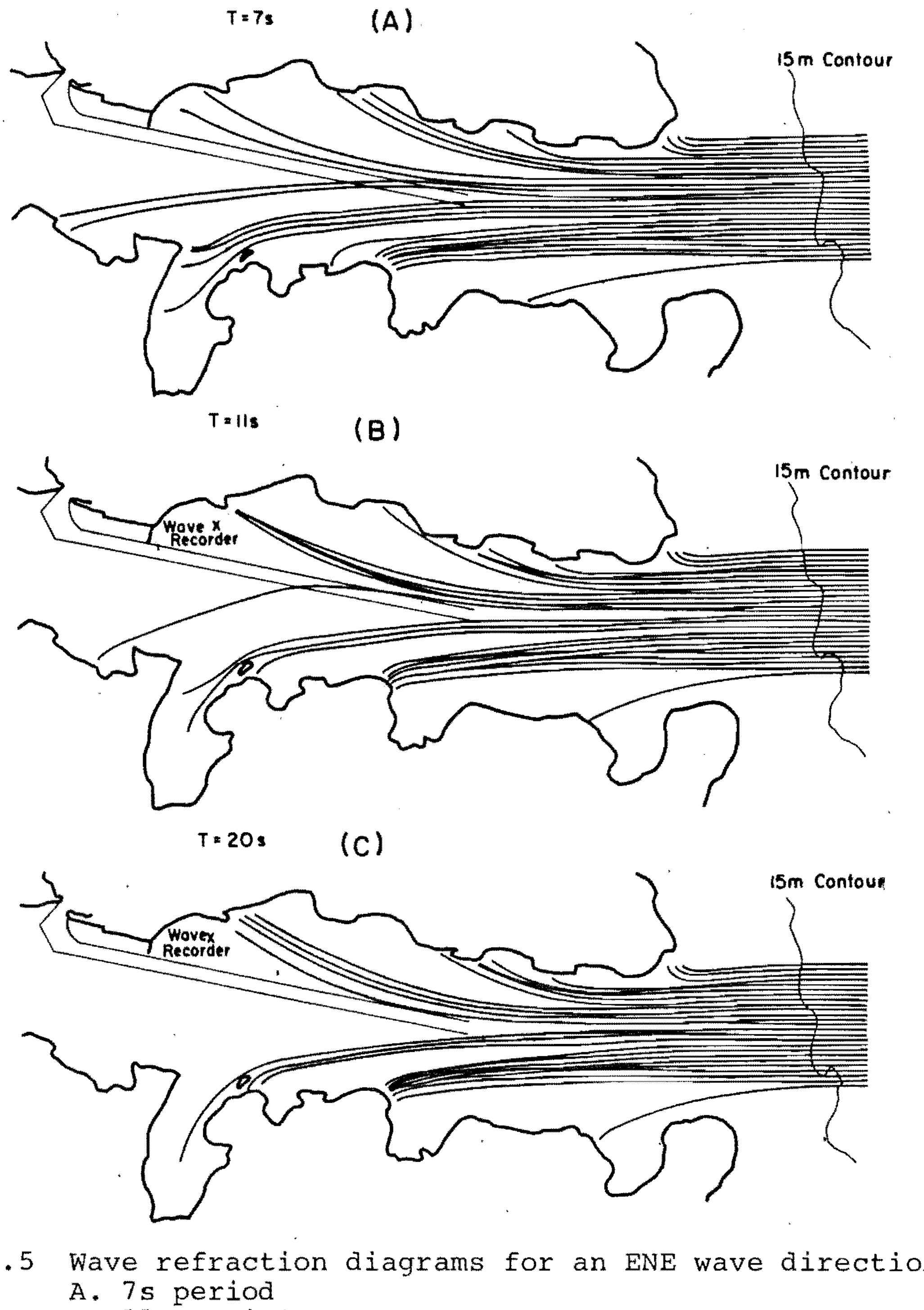


Figure 5.5 Wave refraction diagrams for an ENE wave direction.
A. 7s period
B. 11s period
C. 20s period.

for 20 second waves, and 'effectiveness' figures for 7-12 second waves, it can be concluded from the refraction diagrams that relatively more work will be achieved by the available wave energy on the southern side of the harbour. In fact, because of the sheer rock sides to the harbour, bathymetric data indicate that the only location where refracted 20 second waves will achieve any work on bed sediments is in the entrance to Purau Bay. To all intents and purposes then, the combined occurrences of still water conditions and 20 second waves means that bed sediments will be entrained by wave orbital currents only approximately 47% of the time.

Two further points are worth noting here. Firstly, the absence of refracted waves in Gollans Bay. In itself this may have little effect on harbour dynamics. However, the fact that loss rates for dredge spoil in Gollans Bay (Table 3.6) are the lowest for all dump sites suggests a correlation between erosion and transport of dredge spoil and wave activity. This point will be taken up in section 5.2. Secondly, the refraction diagrams indicate an absence of wave activity in the upper harbour. Observations by the writer and launch drivers are in partial agreement with this. Low swell or long period waves generally dissipate in the vicinity of Camp Bay, while in rougher conditions waves are frequently seen to break on the point at Diamond Harbour opposite the port moles. Undoubtedly waves do enter the upper harbour; the orthogonals in refraction diagrams merely representing a single ray on a wave crest. This is supported by photographs and observed breakers on Quail Island during storms. However the type of waves and the amount of work they achieve will not necessarily be analogous to wave conditions in the lower harbour.

5.1.4 Wind Waves

Lyttelton Harbour is oriented along approximate bearings of 255° (WSW) - 075° (ENE). Dominant wind directions in the region are from the NE, NW, and SW although the upper harbour is protected from NW winds by high cliffs. Thus the dominant winds in the harbour itself are from the NE, with unlimited fetch, and from the SW with a fetch of 8 km to the low tide mark through the valley leading down to Head of the Bay. The wind is channelled by the high cliffs to follow the orientation of the harbour, from both directions between August and April, and predominantly from the SW in May, June and July (see Figure 5.6). Average wind speeds in the three years from 1980-1982 were 5.2 ms^{-1} (10 kts). Speeds exceeded 7.7 ms^{-1} (15 kts) 14% of the time, and 10.3 ms^{-1} (20 kts) only 5% of the time.

For short fetches of 1 to 30 km, wave height increases directly with the wind velocity and the wave period increases as the square root of it (Inman, 1963a). Such would be the case for short period, wind generated waves from the SW in the upper harbour, and having established that only limited longer period wave energy passes the port it seems reasonable to infer that most waves in the upper harbour are wind generated. This would concur with steep, short period chop conditions experienced by launches in moderate to high winds from either direction. Similarly, a pressure type wave recorder moored on the sea bed north of Shag reef in approximately 4 m of water, from 11-4-83 to 2-5-83, recorded no bottom wave motion despite high winds and moderate to rough seas occurring within that period. It is unlikely therefore that wave induced, near-bed currents attain significant

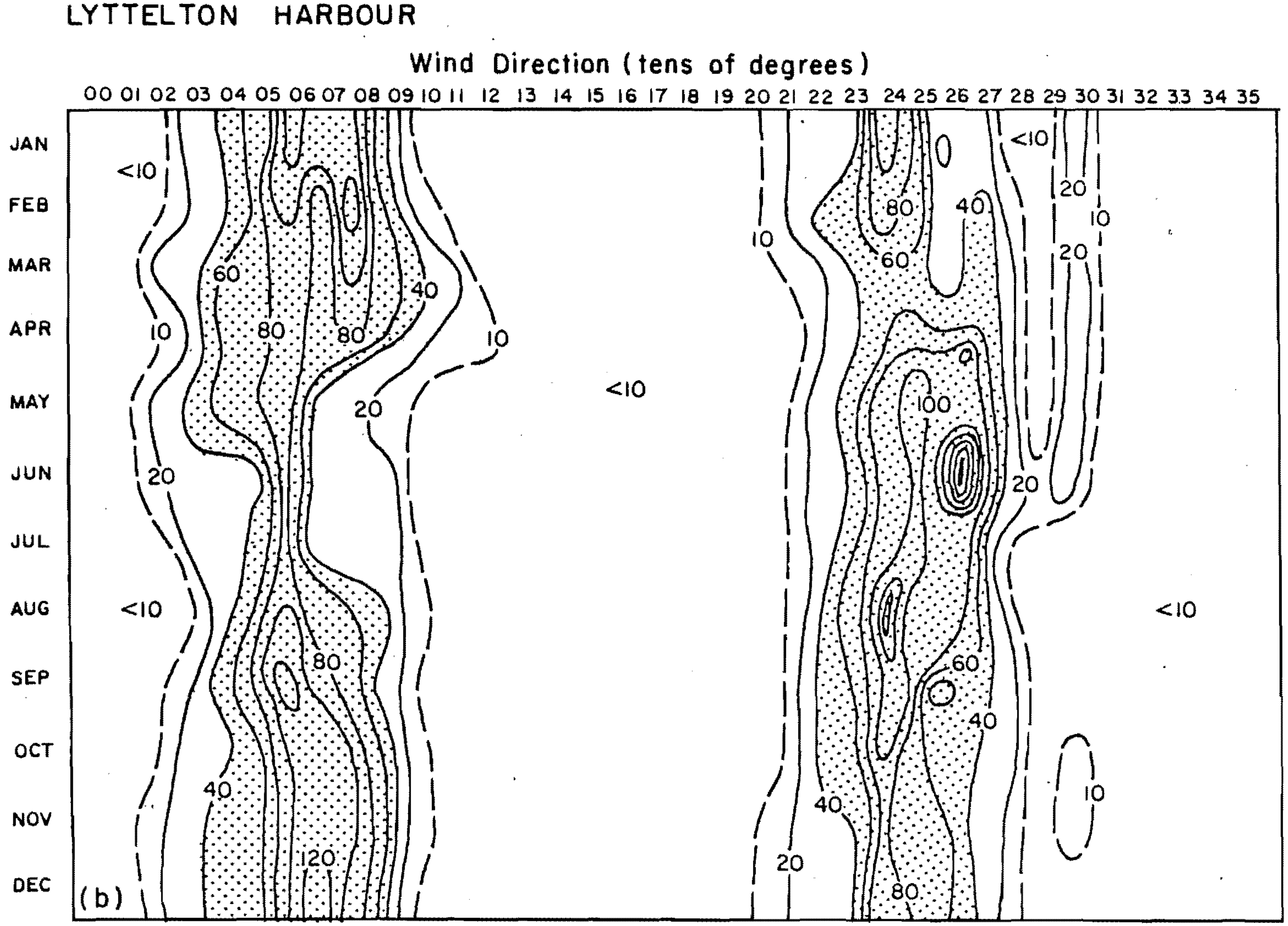


Figure 5.6 Monthly wind direction frequencies for Lyttelton Harbour. Contours are observations per thousand. Source: McKendry (1985).

velocities in the deeper regions of the upper harbour. Short period waves are effective across the expansive tidal regions in Governors Bay, Head of the Bay, and Charteris Bay. In these areas resuspension of fine grained sediments by wind waves may be considerable (Anderson, 1972), and short, steep waves may also provide a major mechanism for foreshore erosion.

The combined influence of wave activity in both the upper and lower harbours will now be assessed within the broader context of the overall hydrodynamic system.

5.2 DISCUSSION: HYDRODYNAMICS AND SEDIMENTATION

5.2.1 Threshold Erosional Velocities

Two previous studies of Lyttelton Harbour have commented on the interaction between hydraulic processes and sedimentation. Brodie (1955) concluded that slightly coarser sediments on the southern side were indicative of more rapid tidal velocities in that locality, while Bushell and Teear (1975) argued the converse on the basis of Hjultstrom's (1939) entrainment velocity diagram shown in Figure 5.7A. In this investigation it has been demonstrated that current velocities vary only slightly across the harbour averaging between 0.2 and 0.3 ms^{-1}. Hjulstrom's diagram shows that sand sized material in the harbour can be entrained by currents between 0.15 and 0.30 ms^{-1}, but that fine silts and clays require greater current velocities to erode them; from 0.70 to 4 ms^{-1} for clays. This may not apply to those areas in the lower harbour with fluid mud layers. Postma (1967) postulates that entrainment velocities decrease for silts and clays as the water content in the sediments, or degree of unconsolidation, increases (see Figure 5.7B). Thus silts and clays with greater than 80% water content (by volume)

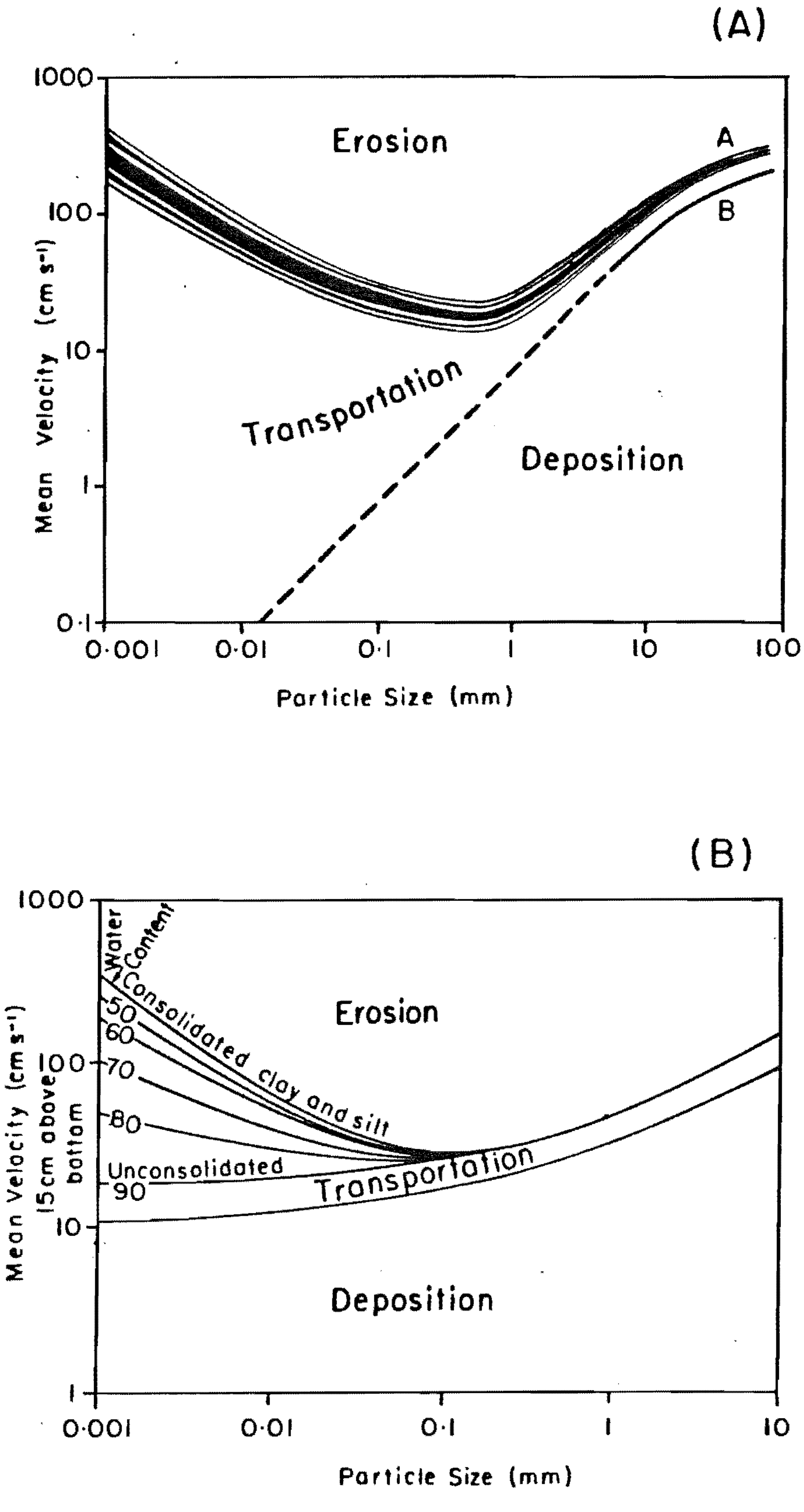


Figure 5.7 Threshold erosion and deposition velocity curves for uniform material.
A. After Hjulstrom (1939)
B. After Postma (1967). Water content is in percentages.

are erodable at velocities comparable to those which will erode the coarser harbour sediments. This applies to all muddy locations in the lower harbour.

From the above evidence two points can be made. Firstly, when near-bed suspended sediment concentrations become low compared to fluid mud levels and water content nears 100% (e.g. 4 $gl^{-1} \approx 99.76\%$ water content) the quantity of sediment in motion is obviously greatly reduced. Effectively, part of the work achieved by currents will be expended directly on the bed where entrainment velocities are high for fine grained sediments. Thus the quantity of fine grained silts and clays in motion near the bed in the upper harbour is relatively small indicating either a rapid rate of sediment transport through the upper harbour system, or more likely a low sediment input into the upper harbour.

Secondly, since sand sized material and unconsolidated fluid muds are equally erodable under similar velocities, the argument pertaining to lateral variations in current velocities cannot be used as a sole explanation for sediment distribution patterns across the lower harbour. Both tidal and wave induced currents are of similar magnitude on both sides of the harbour. The cause of lateral division of the harbour, into finer and coarser sediments, is likely to be a function of the hydraulic ability to transport sediments to an area where they are deposited, rather than the ability to erode sediments from an area and transport them away from it. The distinction is subtle, but vital in sedimentary terms.

5.2.2 <u>The Transition Zone Between Upper and Lower Harbours</u>

The 'neck' of the harbour, the narrowest region between the port and Diamond Harbour of approximately 1.5 km in length and breadth, comprises a transitional region between the dynamics of the harbour above it and the harbour below it. The evidence for this conclusion is examined below.

Clearest evidence is provided by the salinity survey, shown in Figure 4.2A, which portrays the region as a less well mixed zone between two well mixed zones. More importantly, salinity increases in a seaward direction from the upper harbour to a near maximum opposite the port, before declining again near the breakwater and commencing another seaward increase towards a maximum at the harbour mouth. There are thus two salinity maxima along the longitudinal harbour axis representing seaward boundaries to two hydraulic systems.

Further evidence exists from dye tracing and circulation analysis. Layered flow patterns located by dye tracing around Diamond Harbour on the ebb tide confirmed the relatively poor mixing processes operating in the transition zone. Layered flow was not as evident elsewhere in the harbour, and its location near Diamond Harbour coincided with a change from bidirectional currents in the upper harbour to rotatory circulation in the lower harbour. Mid-depth dye contours demonstrated a tendency for ebb currents to partially rotate near Diamond Harbour, in a region inferred to be the point of flow separation which induces the ebb tide circulation. The same area is inferred to be the limit of the flood tide gyre, based on current and tidal data. Thus the narrow 'neck' is also an area of change between upper and lower harbour tidal flow patterns.

Two final indications of a divided harbour can be seen in sediment patterns. Rollability analysis enabled areas of scour and deposition to be located for sand sized material

(Figs. 3.11 and 3.12), and determined depositional zones, or sinks, between Diamond Harbour and the port. For average relative rollability values (whole samples) a strong sink exists directly opposite the breakwater, extending to the east slightly. For the very fine sand fraction two weak sinks exist between Diamond Harbour and the port. In both instances, particularly so for whole samples with coarser sediments, the sinks are located in the centre of otherwise erosional regions of some extent along the southern side of the harbour. Their locations are entirely atypical of surrounding sedimentary patterns and could only be explained by highly local mechanisms.

In Figure 3.15, a near-bed suspended sediment concentration of 5 gl^{-1} opposite the breakwater is again atypical of surrounding conditions. Its location coincides with the whole sample relative rollability sink, and the rotational, ebb tide, layered flow recorded by dye tracing. It is atypical for two reasons. Firstly, it represents a depositional zone of fine mud at a site with coarser sediments, and a relatively high mean grain size (refer Figure 3.8). Secondly, despite the low entrainment velocity required for such unconsolidated material, the mud is being deposited in the centre of a zone identified by rollability as erosional for the coarser sediments. It is evident that the transfer of sediment, of either a coarse or fine nature, from the lower harbour through the so-called transitional region to the upper harbour is not a matter of course, irrespective of flood currents and wave activity. Despite the obvious transfer of tidal and wave energy, and some sediments between upper and lower harbours, ample evidence has been provided to demonstrate a certain independence in the dynamics of the two regions. The cause is found in local hydraulic mechanisms operating between Diamond Harbour and the port.

5.2.3 Sedimentation: Transport, Deposition and Distribution

It was established in chapter four that density currents operating within Lyttelton Harbour are negligible, and are therefore insignificant in sedimentary terms. The processes effecting sedimentation are wave induced and tidal currents.

The action of flood currents, slightly longer than ebb currents on average, and wave induced orbital velocities of over 1 ms^{-1} combine to generate the transport of fine sand on the southern side in an upharbour direction. Both forms of currents attain sufficient velocities to entrain sediment, but the currents induced by steeper storm waves in the region between Camp Bay and Purau Bay, are such that upharbour sand transport is at times extremely rapid, and is a net effect through time. As a result, fine sand is accumulating in Governors Bay, Head of the Bay, and Charteris Bay; particularly around Quail Island in all cases, where strong sinks are found. A lag deposit of very fine sand in the centre of the Head of the Bay indicates some downharbour movement of fines, although these are likely to also be deposited in the region around Quail Island. Erosion from tidal flats in the Head of the Bay will be caused by resuspension of fine sediments by wind waves and will not affect coarser particles to any extent.

Rollability analysis demonstrates a degree of sediment movement seaward in the lower harbour on both sides of the channel, so that a bidirectional transport system exists on the southern side, with a source area in the centre of the transport path. Bearing in mind that wave induced oscillatory currents effect sediment transport less than 50% of the time, ebb tidal currents will transport sediment in a seaward direction to be deposited in the harbour entrance. Kranck (1972; p.599) observes that: "For net sediment transport to occur it is necessary to have either a residual current associated with the tidal stream or an asymmetry in the speed and duration of the tidal streams". The total amount of net transport depends on the relative importance and interaction between the two. Lyttelton Harbour tidal asymmetries are at times marked, but vary considerably so that in the short term (several tidal cycles), net sediment transport may change from a seaward to landward direction or vice versa. In the longer term wave activity will be the deciding factor inducing predominantly upharbour sediment movement.

Tidal asymmetry and wave activity do not offer an explanation for the location of strongly depositional zones in the entrance and adjacent to the breakwater however. Both sites are in exposed, comparatively high energy locations. Nor do asymmetries and wave induced currents supply a reason for lateral, sediment grain size variations across the lower harbour. Einstein and Krone (1962) and McCave (1970) state that fine sediment may be deposited out of currents with velocities of 0.2 to 0.3 ms^{-1}, and later McCave (1971) concluded that the presence of a zone of high wave activity does not inhibit the deposition of mud if concentrations are high. In this case they are high; as evidenced from dredge spoil dumpings and indicated by fluid mud surveys. Thus, given the directional current data obtained and the dearth of any other recorded data, deposition can be accounted for. This explanation would be unsatisfactory though as it really fails to explain sediment distribution or the precise location of depositional zones. The presence of coarser particles on the southern side is most probably due to the erosion of rather unweathered loess on hillslopes, which does not exist on the northern cliffs. Sediment sorting characteristics (Fig. 3.10) tend to support this notion.

The reason why considerably less mud is deposited on the southern side than the north is less readily explained by wave and tidal activity. Although dredge dumpings, comprising fine channel mud, obviously maintain high mud concentrations on the northern side, sediment distributions were similar in previous years (Brodie, 1955) when spoil was dumped on the southern side in Camp Bay and Little Port Cooper. Therefore, while the erosion of sediments can be accounted for by tidal currents, tidal asymmetry, and wave induced currents alone, the transport of sediment within the harbour and its subsequent deposition cannot.

5.2.3.1 Tidal and Sediment Circulation

In terms of net sediment transport, the circulation pattern described in section 4.3 may be regarded as a residual current. It provides a mechanism for net, long term sediment distribution, particularly in the lower harbour. Tidal currents, sediment input from catchment erosion, and upharbour sediment transport accounts for the distribution and rate of accumulation of sediment in the upper harbour in the documented period since 1849.

A major cause of lateral grain size variations in the lower harbour is the circulation of fine sediments, and it is postulated here that the lateral division of the harbour into (verbally defined) mud and sandy-mud (Fig. 3.5) will coincide with shear forces operating along the centre of the gyre. Wolanski et al. (1984) observed that sediment distributions suggested somewhat weaker currents in the wake where fine sands were more stable. In this instance the predicted rotatory currents in the harbour entrance and near the breakwater coincide with stable sink deposits of fine sand, and zones of concentrated fluid mud in the channel. The implications are that under conditions of rotatory currents, little sediment in the lower harbour will escape through the harbour entrance or into the upper harbour. Whilst rollability analysis has demonstrated transport of very fine sand into the upper harbour, this is considered to relate to wave activity with much entrainment of sand occurring within the transition zone itself. The location of a zone of concentrated, near-bed suspended sediment is indicative of the fact that very fine particles are depositing at the western limit of the gyre; or at the point of separation of flow on the ebb tide.

Loss of spoil from earlier dump sites at Camp Bay and Little Port Cooper would have resulted in transport of fine material along the southern side, and its subsequent deposition either at the entrance or in the channel near the breakwater. The strong sink for whole sample rollability near the breakwater suggests that rotatory currents are too weak to transport sand particles across the harbour. Fine material on the other hand is likely to be carried across the harbour by both the rotatory currents and the oblique angle ebb tide currents. Much of it will probably settle into the channel which will tend to operate as a sediment trap. Fine sediments on the northern side of the channel will tend towards the harbour entrance, under somewhat faster ebb tide velocities, where they will be deposited in weaker rotatory currents. On the flood tide and under wave activity, fine particles moving upharbour are again likely to settle out in the channel as they move laterally across the harbour, coinciding with the maximum fluid mud concentration shown in Figure 3.15.

These findings concur with those of Ferentinos and Collins (1979; p.70) who established "...a genetic relationship between the localised [topographical] eddy flows and the formation of the [fine-grained (mud)] deposits". However, the gyre fails to provide a total explanation of fine grained sediment transport. Two important aspects of the sediment distribution patterns cannot readily be accounted for. Firstly, mean grain size contours (see Figure 3.8) indicate a lateral gradation of sediments across the harbour from coarse to finer, rather than an abrupt change from sandier material to mud as indicated by 'verbal' sediment descriptions. This suggests lateral movement of sediment directly across the harbour from south to north, rather than confinement of fines to the northern side by the gyre and the channel. Secondly, no explanation is provided for sedimentation when the gyre is not operating, which may represent the greatest portion of any given tidal cycle (Section 4.3). These two points will be discussed further in chapter six.

5.2.3.2 Channel Siltation

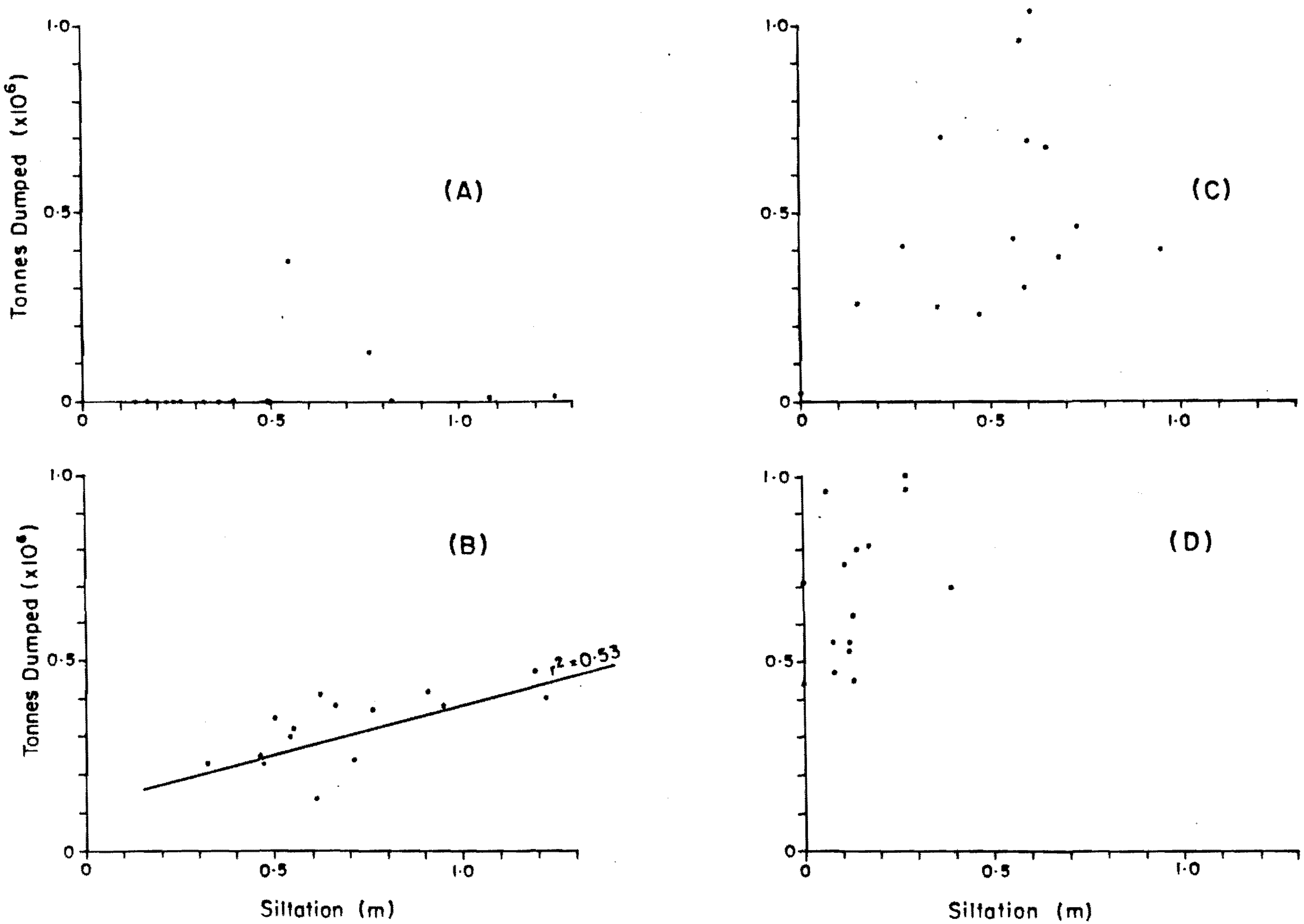
Undoubtedly the greatest supply of sediment within the harbour for channel siltation is from dredge spoil dumped along the northern side. Loss of spoil from these dump sites is approximately equivalent to the quantity dredged annually (Section 3.4.3).

One form of sediment transport which has not been analysed directly in this study is turbidity currents. These are a sedimentary process rather than a hydraulic one, involving mass movement of spoil from the dumping mound across the harbour bed. An attempt to assess this process indirectly involved plotting estimated siltation rates for various channel sections against the quantity of spoil dumped at sites adjacent to those sections. These graphs are shown in Figure 5.8. Centre sections 131-160, overlapping dump sites at Gollans Bay, Livingston Bay, and Breeze Bay (Fig.3.19) have the highest siltation rates, averaging 0.73 and 0.52 m yr^{-1} for sections 131-145 and 146-160 respectively, and a correlation was found to exist for sections 131-145 and dump sites at Gollans Bay and Livingston Bay. An r^2 value of 0.53 (Fig. 5.8B) is statistically significant at the 5% level for a data set of only 16 points (Mills, 1955; p.771).

Spoil loss rate from Livingston Bay has been established as the maximum rate for all dump sites (Table 3.6), and a direct correlation with adjacent channel siltation means turbidity currents must be regarded as a potentially significant form of sediment transport. Consideration of bed profiles in Figure 5.9 reveals bottom slopes at dump sites which are substantially steeper than the natural bed, providing sufficient gradients for mass movement from spoil mounds. It is interesting to note that steeper gradients at Livingston Bay and White Patch Point are comparable, 2.5 - 4.2^{o}, and White Patch Point has the second fastest loss rate of spoil. While there is no significant correlation between the outer channel siltation and spoil dumped at adjacent dump sites, it must be realised that siltation rates are minimal in this region as channel depths are similar to

Figure 5.8 Scattergrams of tonnage of spoil dumped vs siltation rates in channel sections adjacent to the dump site (1968-1983).

A. Gollans Bay dump site. Channel sections 116-130.
B. Gollans Bay and Livingston Bay. Sections 131-145.
C. Livingston Bay and Breeze Bay. Sections 146-160.
D. Breeze Bay, White Patch Point, and Mechanics Bay. Sections 161-175.


(A)
(B)
(C)
(D)
Tonnes Dumped (x10^6)
Tonnes Dumped (x10^6)
Siltation (m)
Siltation (m)
r^2 = 0·53
1·0
0·5
0
0·5
1·0

natural bed levels (Fig. 5.9B). Certainly other data collected demonstrate a pronounced depositional zone in the channel and slightly seaward of White Patch Point. Turbidity currents are discussed further in the following chapter (Section 6.4).

High spoil loss rates are also a function of wave activity between Livingston Bay and White Patch Point, particularly shorter period, steeper storm waves (Fig. 5.5). Minimal wave activity in Gollans Bay, coupled with greater slope gradients and a minimum spoil loss rate, suggests that sediment erosion from the dump sites is a combined function of wave action, tidal currents and turbidity currents. With slightly reduced tidal velocities as well (Table 4.3), spoil gradients in Gollans Bay have established bed profiles indicative of a state approaching equilibrium, more so than at other sites.

The point should be made however, that irrespective of the method of spoil entrainment and transport, the frequent presence of a tidal circulatory system in the lower harbour means that loss of spoil to the open sea will be minimal. Hydraulic and sedimentary data presented earlier indicate deposition of fine grained material in the harbour entrance and in the channel. An estimate for recycling of dredged spoil to the channel in the order of at least 80% would not be excessive.

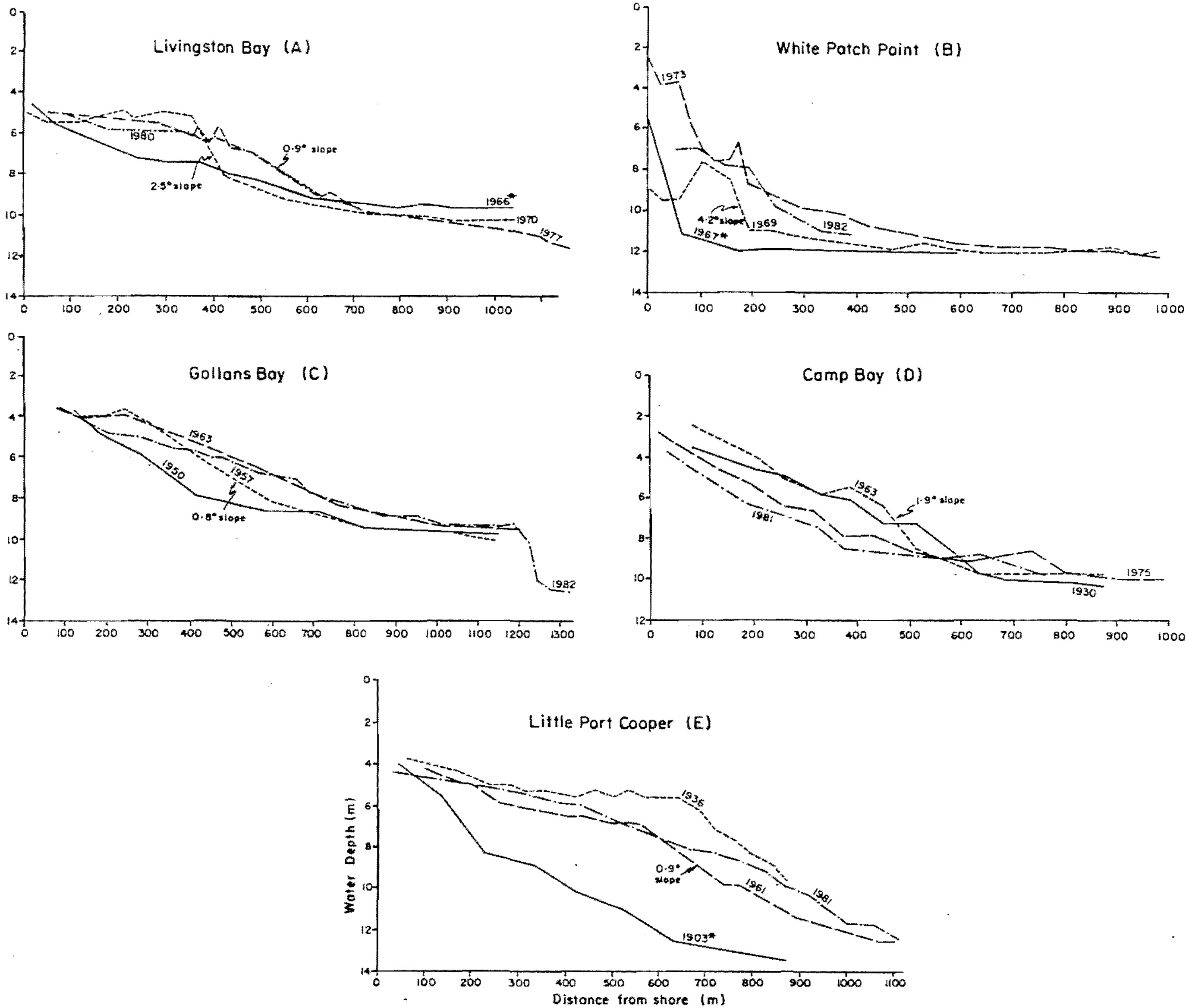
5.3 CONCLUSIONS

Five major conclusions have been drawn from the hydraulic and sedimentary study of Lyttelton Harbour:

(a) Naturally the harbour is in a state of quasi-equilibrium in sedimentary terms, although it tends to be slightly

Figure 5.9 Bed slope profiles at spoil dump sites over time showing changes in slope gradients.

* Shows the date of the last profile prior to the commencement of spoil dumping.


Livingston Bay (A)
1980
0·9° slope
2·5° slope
1966*
1970
1977
White Patch Point (B)
1973
4·2° slope
1969
1967*
1982
Gollans Bay (C)
1963
1950
1957
0·8° slope
1982
Camp Bay (D)
1963
1·9° slope
1981
1975
1930
Little Port Cooper (E)
1936
0·9° slope
1961
1981
1903*
Water Depth (m)
Distance from shore (m)

depositional in the long term. Sediment input from the catchment combined with erosion from areas of the harbour bed are approximately equivalent to depositonal rates in other areas of the harbour. Erosion of the bed is occurring in the centre of the harbour, and deposition at the head of the harbour and in the entrance areas.

(b) Hydraulically the harbour operates in three compartments. These comprise the lower harbour (east of the breakwater), the upper harbour (west of the port), and a centre section between upper and lower harbours which acts as a transition zone between the two. The circulation system operating in the lower harbour does not extend past the breakwater, and wave penetration into the upper harbour is infrequent.

(c) Circulation within the harbour is tidal with no vertical, density driven component. It is therefore essentially two-dimensional in a horizontal plane. The main circulation system operates in the lower harbour in the form of a clockwise gyre on the flood tide and an anticlockwise gyre on the ebb tide. Rotatory currents occur in the harbour entrance and near the breakwater, at either end of the gyre. Its cause is tidal interaction with topography, or harbour geometry. Duration of the gyre varies across tidal cycles depending on tidal variability; ebb and flood tide durations both varying unsystematically between 5.0 and 8.25 hrs. Variables influencing the tidal variability are predominantly weather patterns along the east coast of the South Island, and continental shelf edge waves which oscillate within the harbour at a 2.5 to 3.5 hr period.

(d) Due to the hydraulics, sedimentation and sedimentary processes in the upper and lower harbours have a degree of discreteness. On the southern side of the harbour bidirectional sediment transport occurs, with sediment entering and depositing in the upper harbour. Upharbour transport is most effective and most rapid under wave action, particularly storm waves of 11 second period. Transport is predominantly down-harbour towards the entrance on the northern side.

As a result of the circulation system in the lower harbour, both fine and coarser sediments are deposited between Diamond Harbour and the breakwater, the edge of the transition zone, and at the harbour entrance. This is due to slower velocities in the rotatory currents at either end of the gyre. The gyre is also, at least partially, the cause of accumulation of fine grained sediments on the northern side of the harbour, and the lateral division of the harbour into fine sediments on the northern side and coarser, sandier sediments on the southern side. Gradation of grain sizes in the upper harbour is also from south to north, coarser to finer, however this reflects tidal flow into and out of the three bays, Governor's Bay, Head of the Bay, and Charteris Bay.

(e) The main source of sediment causing channel siltation is from dumped dredge spoil between Livingston Bay and Mechanics Bay. Spoil mounds are eroded by wave action, tidal currents and probably by turbidity currents. Spoil is largely prevented from transport out to sea or into the upper harbour by the gyre, and is instead deposited back into the channel and in the entrance by rotatory currents. Evidence suggests that turbidity currents at Livingston Bay may transport spoil directly back into adjacent channel sections. The quantities of spoil recirculated by wave action and tidal currents, and therefore channel siltation rates, are likely to vary according to weather patterns and tidal variability. Thus the main sedimentary process operating within the harbour, both erosional and depositional, is dredging, the need for which is strongly influenced by factors external to the harbour.

(f) The circulation patterns and sedimentary mechanisms discussed fail to provide a satisfactory explanation for the lateral gradation of mean grain size contours directly across the harbour, normal to the main flow components and parallel to the harbour longitudinal axis. Furthermore, they do not account for sedimentation patterns and mechanisms which must occur when the gyre in the lower harbour is not operating. In chapter three the response in the harbour to dredging was inferred to be short term fluctuations in deposition and erosion of the harbour bed. This chapter and chapter four have identified the hydraulic processes influencing sediment transport and sedimentation. However, in terms of the original questions posed in chapter one, it still remains to establish the processes which control the harbour stability, both now and under natural conditions. This aspect of the dynamics of Lyttelton Harbour will be discussed in the following chapter.

SIX

SEDIMENDATION AND STABILITY

6.1 THE STABILITY CONCEPT

The term stability is generally accepted as a dynamic concept in a geomorphological context, whereby processes and landforms attempt to achieve a short term state of equilibrium. Small changes to the variables affecting either results in an imbalance, and processes then act to restore the equilibrium at a new level. Bruun (1978) defines the stability of inlets in terms of two factors:

(1) The location of the channel (i.e. it doesn't move laterally, or divide into multiples).

(2) The cross-sectional form of the channel (i.e. it maintains a constant depth and width).

He states (p.245):

> The stability of tidal inlets on littoral drift shores should be interpreted as a "dynamic stability" by which the elements involved attempt to maintain a situation characterised by relatively small changes in inlet geometry including location, planform, and cross-sectional areas and shape.

Bruun's theories on inlet stability have been developed for inlets on littoral drift shorelines, and for inlets having unconsolidated sediment boundaries which are thus free to respond to processes in order to achieve stability. Because of the hard rock walls in the harbour, the 'location' factor is irrelevant to Lyttelton since the harbour is laterally immobile. The cross-sectional form of Lyttelton Harbour can be altered. However, Bruun's (1978) stability concepts relating to the form of a channel refer to an optimum condition established between the mobile inlet boundaries, deposition of littoral sediment, and tidal flow through the entrance, preventing closure of the entrance by littoral sediments. There are three reasons why such theories are inapplicable here:

(1) Lyttelton Harbour is not located on a littoral drift shoreline and the external sediment supply is negligible.

(2) The rock walls provide the harbour with only one mobile boundary (at the bed) rather than the three commonly found at inlets on littoral drift shorelines.

(3) The extremely fine grained sediment comprising the harbour bed. For such sediments, "it is not possible to use the principles developed for tidal inlets on littoral drift shores...due to changes in the flow and sediment transport..." (Bruun, 1978; p.11.)

Traditionally, stability has been calculated at the entrance to inlets, utilizing an empirical relationship between the inlet cross-sectional area and the tidal prism. This notion was advanced by O'Brien (1931) and utilized by many others since. Heath (1975) applied the concept to 20 coastal inlets around New Zealand and established an empirical relationship for 16 of them. The gradient of the line in the relationship implies constant mean maximum velocities over a wide range of inlet scales. Where inlet cross-sectional areas increase the tidal prism also increases, and *vice versa*, so that current velocities at the entrance will be proportional to the entrance size. Inlets which fall on the line are therefore said to be stable. Inlets which fall below the line have tidal compartments which are large relative to their cross-sectional entrance areas. These inlets have high entrance tidal velocities, in terms of the derived relationship, and are classified as erosional. By the opposite reasoning inlets which lie above the line are termed depositional. Lyttelton was one of four inlets which was determined as depositional by Heath's relationship. This result was interesting, because all four inlets are of geological origin and possess hard rock walls with only one mobile boundary at the bed. Given that the relationship should reflect changes in the entrance size proportional to changes in tidal velocities, it is a moot point whether such a relationship is applicable to inlets with laterally immobile boundaries. This will be evaluated in section 6.4.

Bruun (1978) has incorporated the entrance area/tidal velocity concept in his work and expanded the theory to include additional variables such as littoral drift. However, like other studies, his work applies properly to the inlet entrance region alone and provides little insight into sedimentation and stability controls within the inlet. Existing approaches to stability necessarily regard sedimentation within the inlet either as the outcome of entrance dynamics, or as a separate, unaddressed issue. In fact the approach is inappropriate for Lyttelton Harbour in any respect because of its rock walls, and also because the entrance area does not present the main stability problem. This occurs well inside the harbour where the channel is deepest, relative to natural bed levels, and where siltation rates are at a maximum. Therefore, it is clearly more pertinent in this study to examine sedimentation and stability within the harbour rather than at the entrance.

Certainly the interaction between the harbour geometry and hydrodynamics, described in chapter four, suggests there may be strong internal stability controls.

6.2 MECHANISMS OF FINE GRAINED SEDIMENT TRANSPORT AND DEPOSITION

In chapter five it was demonstrated that fine grained dredge spoil is recirculated back to the channel by a large tidal gyre operating in the lower harbour. The presence of this gyre cannot, however, offer a satisfactory explanation for the lateral gradation of grain size across the lower harbour, or for the fact that mud is predominantly deposited on the northern side of the harbour but not the southern side. Existing theories for fine grained sediment deposition, examined below, cannot account for the fine grained sediment distribution in the lower harbour.

It is generally accepted that mud, in the form of silts and clays, will be deposited in quiet environments where current velocities are weak and/or turbulence is low. Clearly this is invalid for this situation where velocities on the northern side of the harbour are demonstrably greater than on the southern side, and slack water periods are similar for both areas (refer to section 4.2.2). However, several models provide alternative mechanisms to explain fine sediment deposition and distribution. These are discussed below.

Postma (1961; 1967), and Van Straaten and Kuenen (1958) examined sediment transport (discussed briefly in section 2.2.2) in terms of a "settling lag and scour lag" model for nearshore sediment deposition. Postma (1967; p.163) observes:

> The fine grained suspended matter reacts with a certain inertia to changes of current velocity. Usually there is a time lag between the turn of the tide, when current velocity is zero, and the moment at which the lowest figures for suspended silt are found. This lag can be explained by the fact that in a period of decreasing current velocity, some time is needed for the material to settle. When the current increases, it takes time before the material is resuspended.

Thus, when a flood tide current slows to a point where the suspended sediment content is too great to be carried, part of the suspension will begin to settle. Because silt sinks slowly, it will be transported further in the direction of the current than if settling took place rapidly, and when the current ceases, the settling particles continue to move forward until they are deposited on the bed. This is the settling lag.

The critical erosion velocity of sediment is higher than the transport velocity, so that on the returning ebb tide the same 'parcel' of water which deposited a given sediment particle will be moving too slowly to pick it up again. The particle will be entrained by a 'parcel' of water which was further landward and has had time to reach the critical erosional velocity, but over a given ebb time period this second water parcel will travel a lesser distance seaward before the suspension settles again. This is the scour lag. Over a period of time sediment particles will therefore show a net landward movement, and this will be augmented by the fact that in coastal seas a residual tidal component is often present which causes the amount of water carried over the flood to exceed that carried over the ebb (Postma, 1967).

Van Straaten and Kuenen (1958) observed that the 'lag effect' will produce a net movement of sediment when it occurs in tidal streams that vary in strength from place to place. However, the model, which induces sediment gradations in the direction of flow, is unsatisfactory for explaining sediment distributions in Lyttelton where gradations in grain size are perpendicular to the direction of flow.

McCave (1970) provides an alternative model, mentioned in section 5.2.3, whereby suspended sediment is deposited from tidal currents without the requirement that the suspension settles out only when velocities are slow. Thus the model provides for quasi-continuous deposition, and is formulated on the assumption that there is a plane parallel and close to the bed through which particles can only settle, and once below this plane they must settle to the bottom. In other words, "...the viscous sublayer of the turbulent boundary layer accepts sediment by settling but does not eject it back into the main flow". Using this model suspended sediment may be deposited by tidal currents of up to 0.30 ms^{-1} (1 m above the bed). McCave (1971) also states that if sediment concentrations are high, mud may be deposited in regions with high wave activity at the bed based on the same assumptions as those outlined above.

This model is particularly relevant to the Lyttelton situation where fine sediment exists in high concentrations near the bed, and silts and clays are being deposited under conditions of high velocities and wave energy. However, the model fails to account for the fact that fine grained sediment is not being deposited on the southern side of the channel as well. The dumping of dredge spoil on the northern side does not explain the situation since Brodie (1955) observed the same sediment distributions as the contemporary patterns, at a time when spoil was being dumped on the southern side of the harbour in Camp Bay and Little Port Cooper. Furthermore, the model cannot account for the sediment grain size contours grading across the harbour normal to the main flow.

Bokuniewicz (1980) has postulated a further transport model based on sediment fluxes. Sediment flux is here defined as the 'rate' of sediment transport, and is a function of current velocities which control the hydraulic transport 'capacity' at a given location. The transport capacity refers to the maximum sediment load which a given current is competent to carry.

Bokuniewicz argued that because the rate of sediment transport is a power function of the associated current velocities, very small asymmetries in the speeds of ebb and flood tides at a given location would produce large, net rates of sediment transport in the direction of the faster current. The concept is of less importance for suspended sediment than for bed sediments because the settling lag effect tends to produce a net transport of suspended sediment from regions of swifter currents to areas of slower currents, as explained earlier.

However, with respect to bedload transport, Bokuniewicz (1980; p.108) states:

> The lag times for sand grains may usually be neglected, and the one-way motion of sand depends upon another mechanism that is due to the nonlinear relationship between the sediment flux and the speed of the transporting current. The sediment flux goes as the current speed to some power... Small differences in the speeds of the ebb and flood tides at the same place, therefore, produce large net sediment fluxes in the direction of the swifter current.

In Lyttelton Harbour, where near-bed suspended sediment concentrations are high and constitute a fluid mud layer in some areas (as shown in section 3.3.3), lag settling times will be minimal and fine grained muds may respond in a manner approximating coarser bedload material. Since the swiftness of tidal currents is variable from place to place throughout the harbour, (see Table 4.3) and given that average velocities are slightly higher on the northern side where mud is accumulating, it was felt that the basic concept of the Bokuniewicz model was applicable to Lyttelton. Accordingly, sediment flux values throughout the harbour were calculated, and a model for fine grained sediment deposition in the harbour is proposed in section 6.3.

6.2.1 Sediment Flux Differentials in Lyttelton Harbour

Sediment flux was calculated for the 12 main current stations situated around the harbour (Fig. 4.10). The main data input comprised mean velocities at each station for both ebb and flood tides, recorded at 1 m to 1.5 m above the bed, (Table 4.3) and near-bed suspended sediment concentrations at 5 cm above the bed (see Figure 3.15). Where suspended sediment sampling was not conducted at current stations, estimates of concentrations were made from the nearest sample sites, and from a knowledge of bed conditions at current stations acquired from bed inspection by diving. Near-bed boundary conditions are listed in Table 6.1.

An important constituent in the calculations was the Chezy coefficient, C. This is a friction factor relating to the hydraulic radius, bed slope and flow velocity in open channel flow. Alternatively, by applying the continuity principle, it may be expressed in terms of flow rate and relates to discharge and cross-sectional area rather than velocity. In determining the stability of inlet entrances, Bruun and Gerritsen (1960) established a close approximation for C by the formula;

$$C = 30 + 5 \log A$$

where: C is expressed in $m^{\frac{1}{2}}s^{-1}$

and A = cross-sectional area in m^2.

Since the desire was to establish sediment flux values at all current stations around the harbour, and thereby the internal stability of Lyttelton Harbour, C was determined for each station corresponding to the harbour width at that location. Table 6.1 lists specifications of the harbour at each current station location, and Table 6.2 lists C values for each station.

Calculations were also made for the harbour entrance proper. Near-bed suspended sediment samples had been obtained in several areas within the entrance. However no velocity data existed, and these had to be calculated using the formula from Bruun (1966);

$$\bar{v} = \frac{2\Omega}{AT}$$

where: $\bar{v}$ = mean velocity (ms^{-1})

Ω = tidal prism (m^3)

T = time (seconds)

For spring tides and an average tidal duration of 6.24 hrs, either ebb or flood, a mean velocity of 0.22 ms^{-1} was calculated. Sediment flux values were calculated using this velocity to represent an average maximum flux for the harbour entrance. However, tidal variability discussed in section 4.2.1.1 means this value is not typical of all occasions. Velocity and flux values were therefore calculated for a variety of tidal conditions for the harbour entrance and these are listed in Table 6.3.

Prior to the calculation of flux values, the near-bed shear velocities had to be calculated for each station. Shear

Table 6.1 Harbour dimensions and conditions used in calculating the Chezy coefficient and sediment flux values.

Station No.	Depth at Station (m)	Harbour Width (Km)	Cross-Sectional Area, A (m)	Bed Conditions at Station*
1	3.94	1.550	6,030	Rough
2	6.64	1.625	13,181	Rough
3	7.14	1.950	16,712	Rough
4	7.44	1.975	16,447	Rough
5	8.34	2.425	15,690	Rough
6	11.24	2.625	24,019	Rough
7	8.44	1.750	14,038	Rough
8	8.44	1.975	16,447	Rough
9	6.94	2.425	15,690	Rough
10	8.24	2.125	18,346	Smooth
11	8.94	1.900	18,454	Smooth
12	7.64	2.050	21,434	Smooth
Harbour Entrance	14.53	2.000	29,055	Smooth

* 'Rough' refers to the presence of ripple bedforms and 'smooth' implies a flat bed where fluid mud is present.

velocity is related to the shear stress which is a measure of the stress applied to the bed by water particles flowing over it. Shear stress is calculated from:

$$\tau = \frac{\rho g V^2}{C^2}$$

where: τ = shear stress (kgm^{-2})

ρ = density of sea water (1070 $kg.s^2m^{-4}$)

g = acceleration of gravity (9.81 ms^{-2})

Then shear velocity is obtained from:

$$V_* = \sqrt{\frac{\tau}{\rho}}$$

where V_* is expressed in ms^{-1}. (The shear velocity in this instance has been calculated differently to that in chapter four where it has been designated U_*, although the velocities are in fact comparable.) Values of τ and V_*, are listed in Table 6.2.

Figure 6.1 shows a predictably strong correlation between shear stress and mean velocity. Logically, when velocity is zero there can be no applied stress so a regression equation on the data points was forced through zero using the "mirror-image" data set technique outlined by Hands (1983). The resultant function was a very weakly determined power curve. Data were lacking for low velocities, and inspection of a hypothetical curve in Figure 6.1 suggests that the fitted power function may be statistically stronger if the data set included values closer to zero. The implications for bed stress, and therefore sediment entrainment, are far greater on the hypothetical power curve than for a straight line relationship. This is the more so where small differences which exist at higher velocities between the various stations, or between ebb and flood portions of the tide, can produce

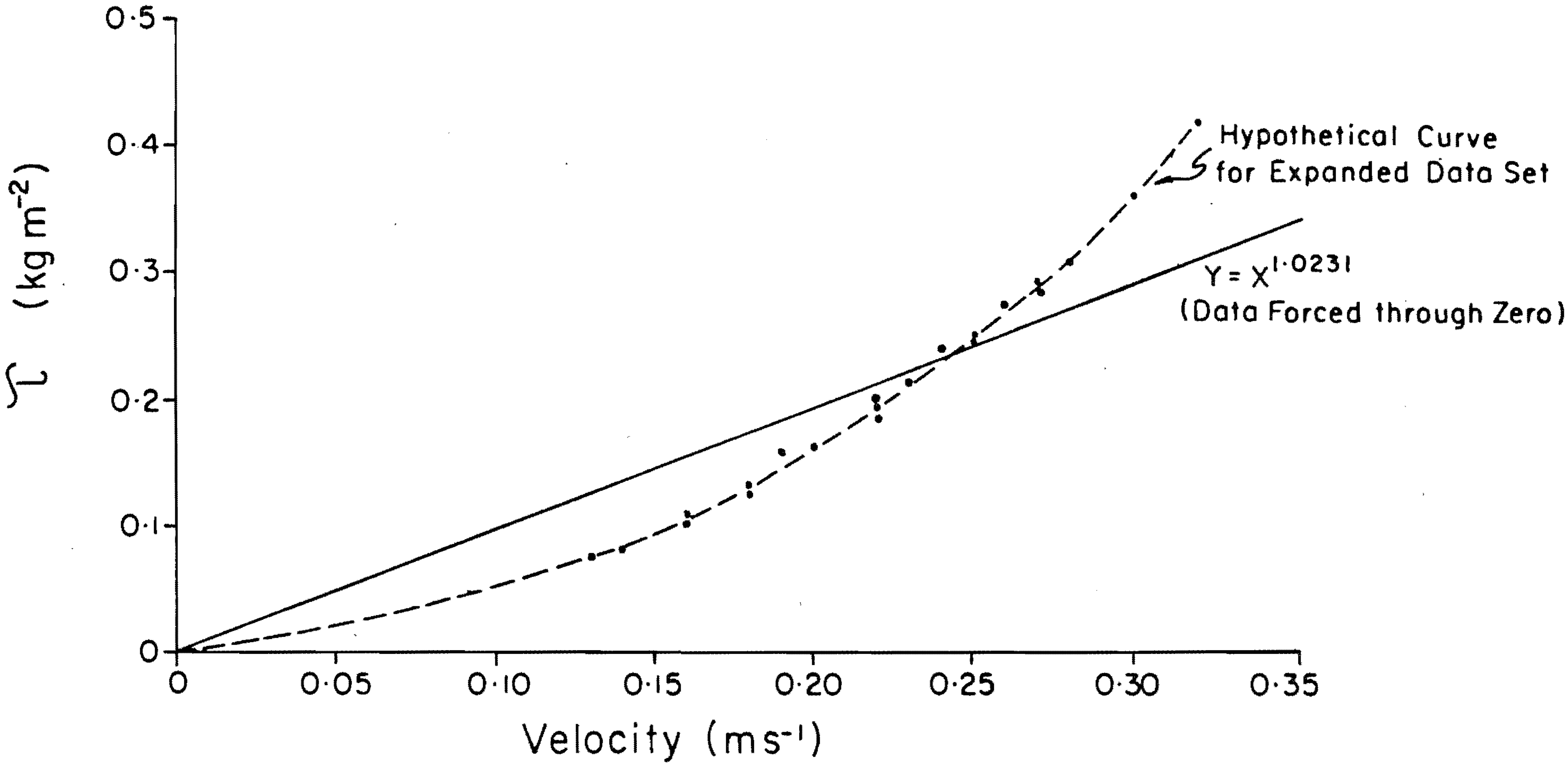


Figure 6.1 Relationship between calculated shear stress values and current velocities in Lyttelton Harbour.

large differences in sediment flux.

Sediment flux was calculated at each station and at the harbour entrance using the formula outlined in Bruun (1978) and Nordin and McQuivey (1971):

$$q_s = \gamma V_* C_a \int_a^D \left[\frac{a}{D-a} \cdot \frac{D-y}{y} \right]^z \left[2.5 \ln \left(\frac{y}{k_s} \right) + 8.5 \right] dy$$

where: q_s = suspended sediment mass transport (flux; m^3s^{-1})

γ = specific gravity (ρg; kgm^{-3})

C_a = suspended sediment concentration at a distance 'a' above the bed (ppm; Bruun, 1978; p.210).

a = a distance above the bed, in this case 5 cm.

D = depth of flow taken to be the water depth (MSL) at each station (m).

k_s = height of the roughness elements on the bed (m)

z = $\omega/\beta\kappa V_*$ (the Rouse number)

ω = particle fall velocity (taken as $3.901 \times 10^{-4} ms^{-1}$; Lyttelton Harbour Board)

β = a coefficient to allow for diffusion of particles (approximately equal to one for fine particles).

κ = von Karman's velocity constant (taken as 0.4).

The equation is derived from the one-dimensional diffusion equation describing the suspended sediment concentration profile (left brackets), and a logarithmic velocity distribution describing the velocity profile (right brackets).

Variations in bed conditions, rough or smooth, affected the velocity profile in terms of the y/k_s component. For rough boundary conditions, k_s was taken as 0.0088 m, from bedform ripples measured by the author at 6-10 cm wavelengths (λ). The height of the ripples (k_s) was taken as an average value where

$$k_s = 0.074\ \lambda^{1.19} \qquad \text{(Allen, 1977)}$$

Table 6.2 Characteristics for flux calculations, and flux values for tidal current stations and harbour entrance.

Station Number	Tide State	Chezy Coefficient C, ($m^{\frac{1}{2}}s^{-1}$)	Shear Stress τ, (kgm^{-2})	Shear Velocity V_*, (ms^{-1})	Rouse Number, Z	Near Bed Sediment Conc. Ca, (ppm) (x 10^{-9})	Sediment Flux q_s, (m^3s^{-1}) (x 10^{-5})
1	Ebb	48.902	0.074	0.008	0.12	0.136	0.058
	Flood		0.158	0.012	0.08		0.099
2	Ebb	50.600	0.080	0.007	0.11	0.194	0.153
	Flood		0.105	0.010	0.10		0.181
3	Ebb	51.116	0.194	0.014	0.07	4.658	7.78
	Flood		0.231	0.015	0.07		8.34
4	Ebb	51.084	0.213	0.014	0.07	0.275	0.479
	Flood		0.272	0.016	0.06		0.576
5	Ebb	50.978	0.214	0.014	0.07	0.275	0.540
	Flood		0.214	0.014	0.07		0.540
6	Ebb	51.903	0.126	0.011	0.09	7.235	13.70
	Flood		0.284	0.016	0.06		23.40
7	Flood	50.736	0.418	0.020	0.05	0.245	0.771
8	Ebb	51.084	0.195	0.014	0.07	0.918	1.83
	Flood		0.103	0.010	0.10		1.10
9	Ebb	50.978	0.162	0.012	0.08	0.918	1.21
	Flood		0.131	0.011	0.09		1.06
10	Ebb	51.318	0.291	0.017	0.06	55.05	121.0
	Flood		0.249	0.015	0.07		101.0
11	Ebb	51.331	0.359	0.018	0.05	29.31	79.60
	Flood		0.211	0.014	0.07		54.00
12	Ebb	51.656	0.308	0.017	0.06	73.62	150.0
	Flood		0.246	0.015	0.07		124.0
Entrance	Average Springtide	52.316	0.186	0.013	0.08	32.01	85.70

Table 6.3 Entrance velocity, stress, and flux characteristics for various tidal conditions.

Tide Duration (Hrs)	Tide Range*	Velocity (ms^{-1})	Shear Stress (kgm^{-2})	Shear Velocity (ms^{-1})	Rouse No.	Sediment Flux ($m^3s^{-1}x10^{-5}$)
6.24	Spring	0.22	0.186	0.013	0.08	85.7
	Neap	0.19	0.139	0.011	0.09	67.4
5.00	Spring	0.28	0.301	0.017	0.06	129.0
	Neap	0.24	0.221	0.014	0.07	98.7
8.00	Spring	0.17	0.111	0.010	0.10	57.1
	Neap	0.15	0.086	0.009	0.11	47.7
5.00	2.50m	0.36	0.497	0.022	0.04	193.0
7.75	1.35m	0.12	0.055	0.007	0.14	31.4

* Normal ranges: Spring 1.92m

Neap 1.67m

Bruun (1978) utilized a corrective parameter in his y/k_s term. This is equal to one for rough boundary conditions (Einstein, 1950; Fig.4), and was ignored for smooth boundary conditions because of the fluidity of near-bed sediment. Instead, for smooth boundary conditions,

$2.5 \ln\left(\frac{y}{k_s}\right) + 8.5$ became $2.5 \ln\left(\frac{y}{\nu}\sqrt{\frac{\tau}{\rho}}\right) + 5.5$ (Allen, 1977; p.39)

where ν is the kinematic viscosity of sea water and is taken to be $1.20934 \times 10^{-4}\ m^2 s^{-1}$ (Miyake and Koizumi, 1948) at a temperature of $13^{\circ}C$, the average annual water temperature in Lyttelton Harbour.

Calculated flux values are listed in Table 6.2, and in Table 6.3 for varying tidal conditions at the entrance. The most striking feature of these figures is the fact that four orders of magnitude separate the maximum and minimum flux values within the harbour. This point is important for two reasons. Firstly, it is obvious that very large flux gradients exist between a number of tidal stations implying marked changes in rates of sediment transport around the harbour. Secondly, the magnitude of differences between stations are such that they exceed the error magnitude involved in the flux calculations. Flux values can only be regarded as estimates since the near-bed suspended sediment concentrations were obtained from single samples at each location, and mean velocities were used to represent velocity variations across the tidal cycle. Thus figures in Table 6.2 and 6.3 represent instantaneous flux.

Figure 6.2 depicts a plot of flux versus velocity for Lyttelton with a regression equation (A) fitted to the data. Station numbers for each plotted value show a clear division in the centre of the graph between fine grained sediments (high

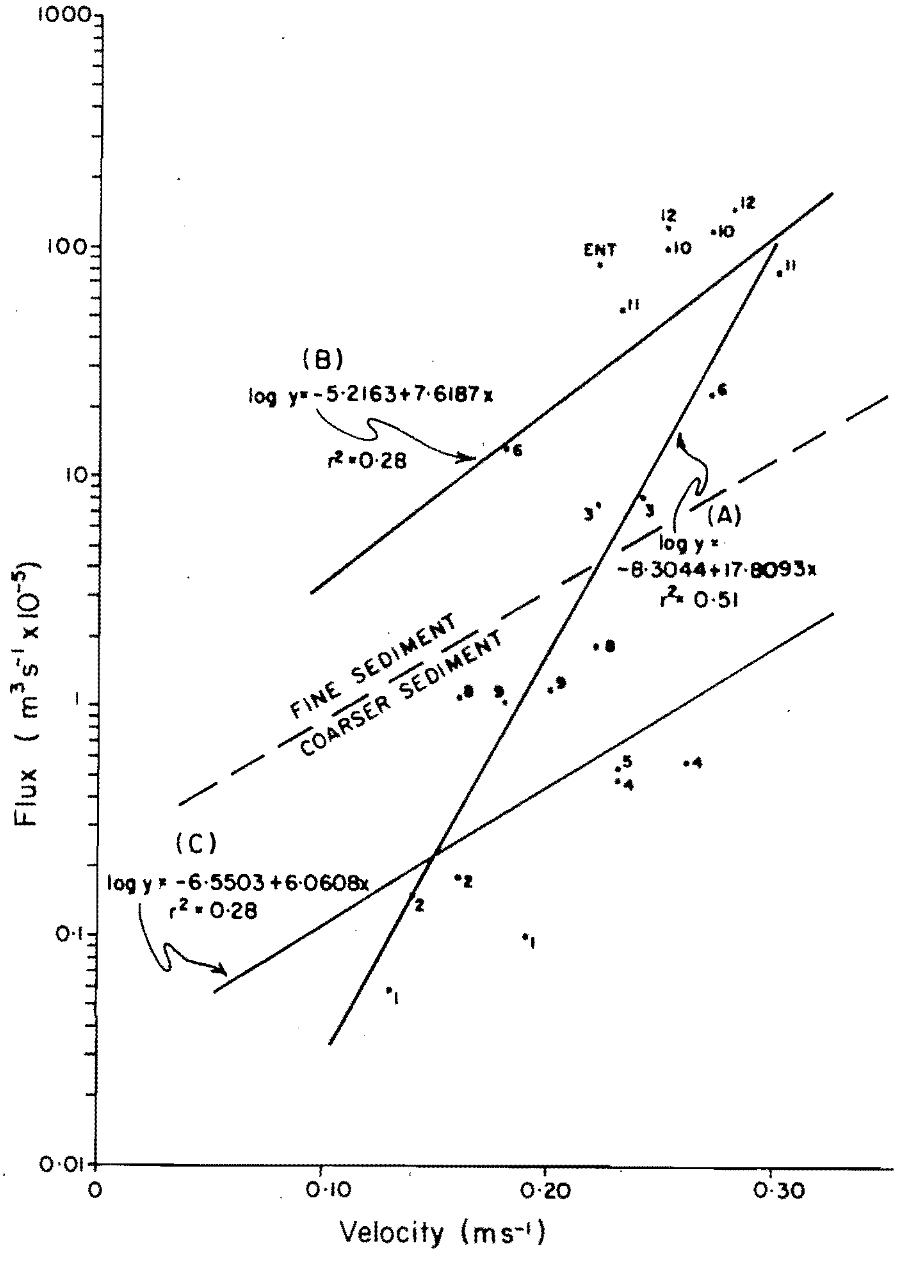


Figure 6.2 Scattergram of mean velocity vs flux with regression equations applied to the total sample (A); fine grained muds (B); and coarser sandier sediments (C).
Station numbers are shown for each plot.
ENT is the entrance plot.

flux) and coarser sediments (low flux). It is also apparent that the regression equation overestimates flux where suspended sediment is low and underestimates it for fluid mud regions. Accordingly the graph was divided into two sections and regression equations were fitted to high and low flux regions. Although the correlations for the two equations (B and C) are low, the lines fitted are interesting in that they have similar gradients and are effectively separated by the initial flux level, or y intercept, which is an order of magnitude greater for fine, high flux sediments. The implication of this is that large differences in flux magnitudes around the harbour reflect variations in sediment supply. That is, tidal flow is under supplied with suspended sediment in sandier areas, and therefore flux is low, while there is an ample or over supply of fine sediment in muddy areas where flux is high.

Power functions were applied to the regression curves, with the data again forced through zero using Hands' (1983) technique. Figure 6.3 shows the resultant curves for change in flux with change in velocity. Predictably the power function coefficient for fine grained muds (B) is considerably greater than for either of the other two curves. Thus for flow velocities greater than about 0.25 ms^{-1}, small variations in velocity will lead to extremely large changes in flux for fine grained suspended sediment in high concentrations. Current stations 10, 11 and 12 between Gollans Bay and White Patch Point exhibit these characteristics, with mean ebb and flood tide velocities varying between 0.23 and 0.30 ms^{-1} and very high, near-bed concentrations of suspended sediment. Very small variations in velocities between these sites, and away from each site in any direction, will have considerable

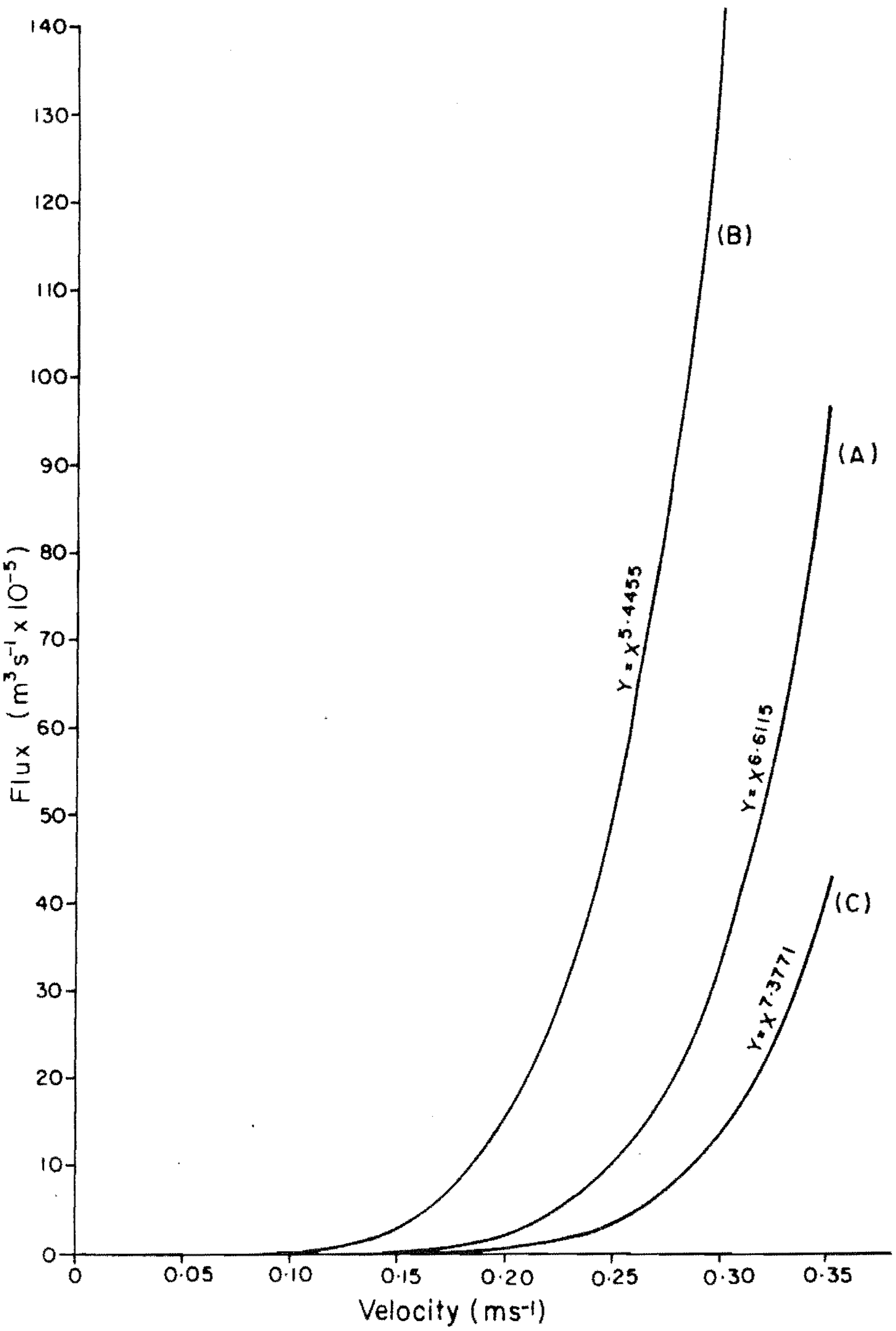


Figure 6.3 Power functions of the velocity/flux regression curves in Figure 6.2 with the data forced through zero.
A. Total sample
B. Fine grained muds
C. Coarser sandier sediments.

implications for entrainment and deposition in terms of rapid changes in flux between any two locations. These effects can be illustrated in the form of a sediment transport/deposition model for fine material.

6.3 THE DYNAMIC TRAP: A DEPOSITIONAL MODEL FOR FINE SEDIMENTS

As Van Straaten and Kuenen (1958) note when describing net suspended sediment movement, at the moment a current reaches its maximum velocity at a given point, the water particles that pass over this point have already started to slow down. Correspondingly, where the suspended sediment load is large, material will begin to be deposited immediately the point of maximum velocity has been passed and the transport capacity of the flow begins to decline. This phenomenon forms the conceptual basis for the Dynamic Trap model, where a dynamic trap is defined as an area of sea bed where sedimentation is controlled by energy boundaries in the form of flux gradients.

The concept of fine sediment deposition near the maximum flow regions, rather than in quiet areas, has been represented in conceptual form in Figure 6.4A and B. As illustrated in Figure 6.4A, when velocity increases the transport 'capacity' increases, and therefore the flux gradient is positive. At the point of maximum flow the maximum transport capacity is reached and, given a sufficient sediment supply, the maximum transportable sediment load is attained. Any addition of sediment to the system under maximum load conditions will cause the capacity to be exceeded and deposition will occur before, and at, the point of maximum flow. Deposition also occurs as soon as velocity begins to decrease, when transport

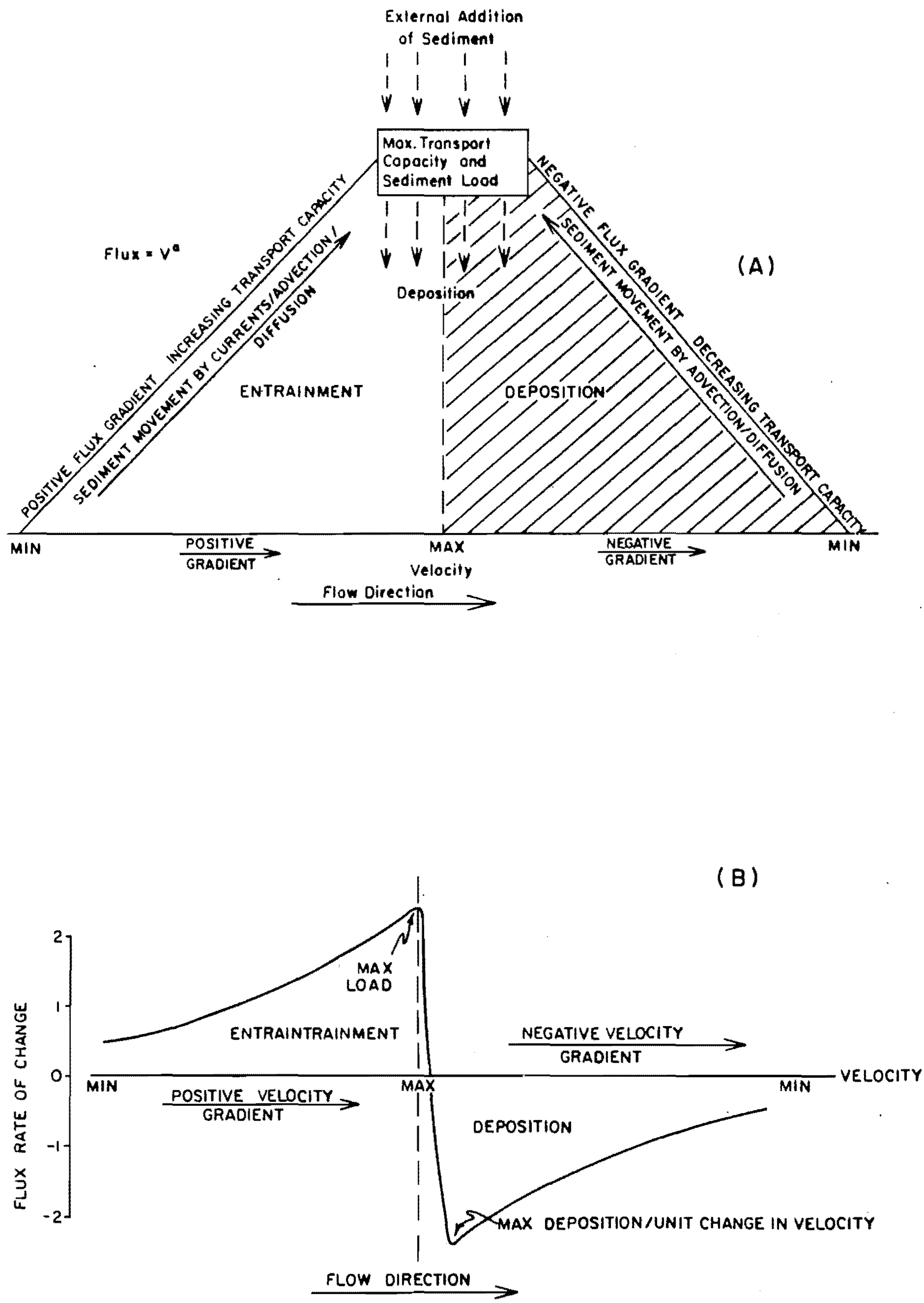


Figure 6.4 The Dynamic Trap: A model for fine grained sediment transport and deposition under conditions of high near-bed suspended sediment concentration.
A. The conceptual model.
B. A hypothetical curve for entrainment and deposition in terms of the model.

capacity decreases causing a negative flux gradient. Clearly deposition will be greatest, and most rapid, when near-bed suspended sediment concentrations are high and the transportable load continues to be exceeded as velocity declines. If suspended sediment concentrations are low, then lesser flow will continue to carry the load and deposition will not occur.

Examination of Figure 6.3B, for high suspension concentrations in Lyttelton, reveals the greatest rate of change in flux per unit change in velocity occurs for the highest velocities, which is logical for a power function. The resultant effect of this in terms of the model is that the maximum sediment load is achieved by the point of maximum flow, and maximum deposition per unit reduction in velocity occurs immediately after the point of maximum flow has been passed. Figure 6.4B portrays a hypothetical curve for entrainment and deposition, showing the point of maximum deposition of fine mud sediments to be near the point of maximum velocity. As flow velocity continues to decrease the magnitude of sediment deposition also decreases, corresponding to a decline in the rate of change in flux per unit change in velocity which is at a minimum at the lowest velocity reached.

The model is examined for actual data along the northern side of Lyttelton Harbour, between Gollans Bay and the entrance, in Figure 6.5 and 6.6A and B. Figure 6.5 shows a hypothetical curve based on flux as a power function of velocity while Figure 6.6A depicts calculated flux values for each station. In the latter the model can only be applied between White Patch Point and the harbour entrance in terms of velocity gradients, although a decreasing flux gradient between stations 10 and 11 still demonstrates deposition at high velocities.

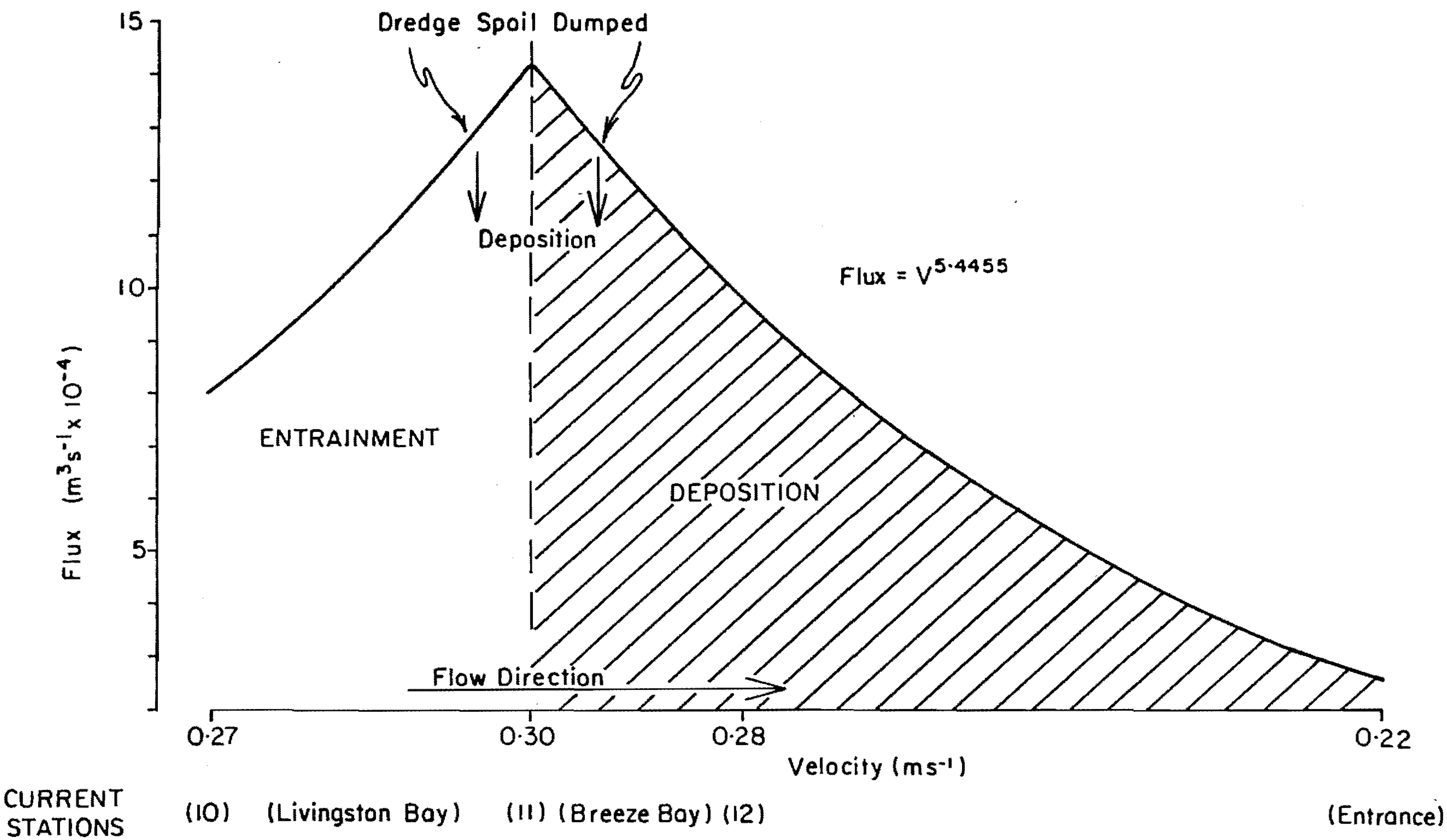


Figure 6.5 The Dynamic Trap model applied to flux values, as a function of mean ebb tide current velocities at current stations 10, 11, 12, and the harbour entrance.

As argued for the model, such deposition under conditions of increasing velocity may be due to excessive addition of sediment to the system, from dumping of spoil in a region where flow is already near its transport load capacity. Entrainment under negative velocity gradient conditions, between stations 11 and 12, is also contrary to the ideal model but may be explained in flux terms. If the quantity of sediment deposited between stations 10 and 11 was large so that the sediment load of the current passing station 11 was minimal, then entrainment would continue to occur at the indicated velocities until transport capacity was maximised, despite the fact that the velocity gradient was negative between stations 11 and 12. Thus the model is dependent on both velocity gradients and sediment supply and will not always follow strictly the indicated or implied velocity gradients. The degree of entrainment or deposition between any two locations is therefore directly dependent on the magnitude of the change in flux between those two locations.

Figure 6.6B shows flux as a function of distance between stations. Logically, the distance over which a given velocity gradient occurs will affect the rate of entrainment or deposition in terms of the change in flux per unit distance. Comparison of the implied rates of entrainment and deposition (slope of the line) in Figure 6.6B with Figure 6.6A shows a marked reduction in the rate of entrainment between stations 11 and 12 and a marked increase in the rate of deposition between station 12 and the entrance. Actual rates of entrainment and deposition can be expressed by this means if one regards the distance component as a metre wide strip of bed so that flux becomes a function of a unit area of bed. Then rates of erosion and deposition for the various harbour locations may

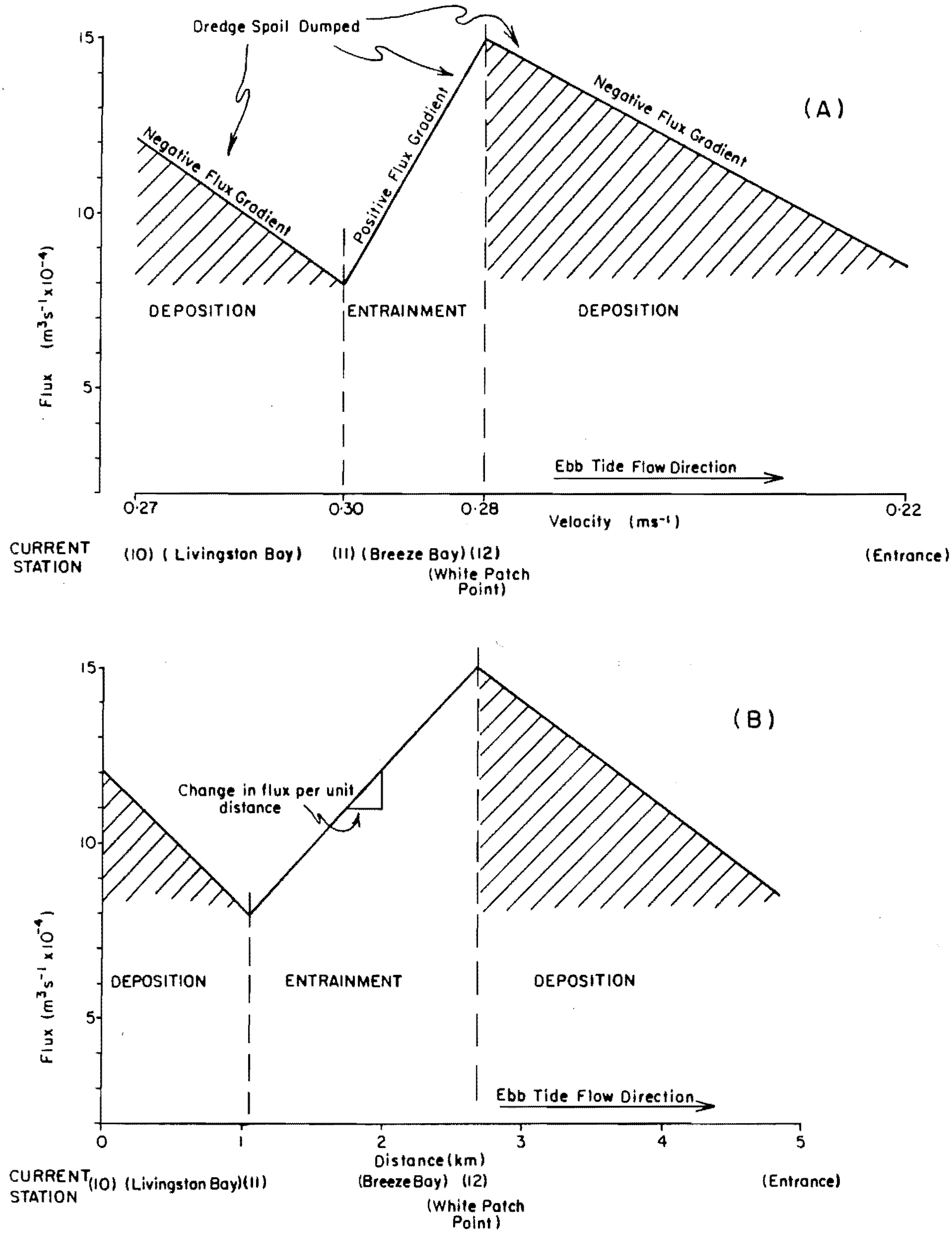


Figure 6.6 Calculated flux values applied to the Dynamic Trap model as a function of:
A. Velocity gradients between stations
B. Distance between stations.

be expressed by the ratio $(F_1-F_2)/D$ where F_1 and F_2 are the respective fluxes of stations 1 and 2 in the direction of flow, and D is the metre wide distance between the two. Mapping these values produces a spatial illustration of erosional and depositional areas, showing their relative magnitudes, and reflects the internal distribution of fine grained suspended sediments.

6.4 STABILITY OF LYTTELTON HARBOUR

Figures 6.7A and B depict the calculated flux values at each current station and the $(F_1-F_2)/D$ ratio between stations for ebb and flood tides respectively. The spatial patterns show high rates of suspended sediment deposition on the northern side of the harbour at Livingston Bay and the entrance on the ebb tide; and on the flood tide, on the northern side at Breeze Bay and the eastern side of Gollans Bay, and the southern side between the entrance and Purau Bay. Moderate deposition rates exist directly opposite the breakwater on both tides, the ebb tide rate being marginally greater than the flood rate. On the ebb tide a weak depositional zone exists on the western side of Gollans Bay, while regions of similar rates are found between Battery Point and the breakwater and in the upper harbour on the flood tide.

The plotted results are interesting when compared with deposition patterns established from relative rollability analysis (see Figures 3.11 and 3.12). Rollability analysis was conducted on sand particles only but a strong similarity exists in the general patterns of deposition and erosion exhibited by the fine grained flux data and the rollability data. Both sets of data demonstrate varying degrees of deposition

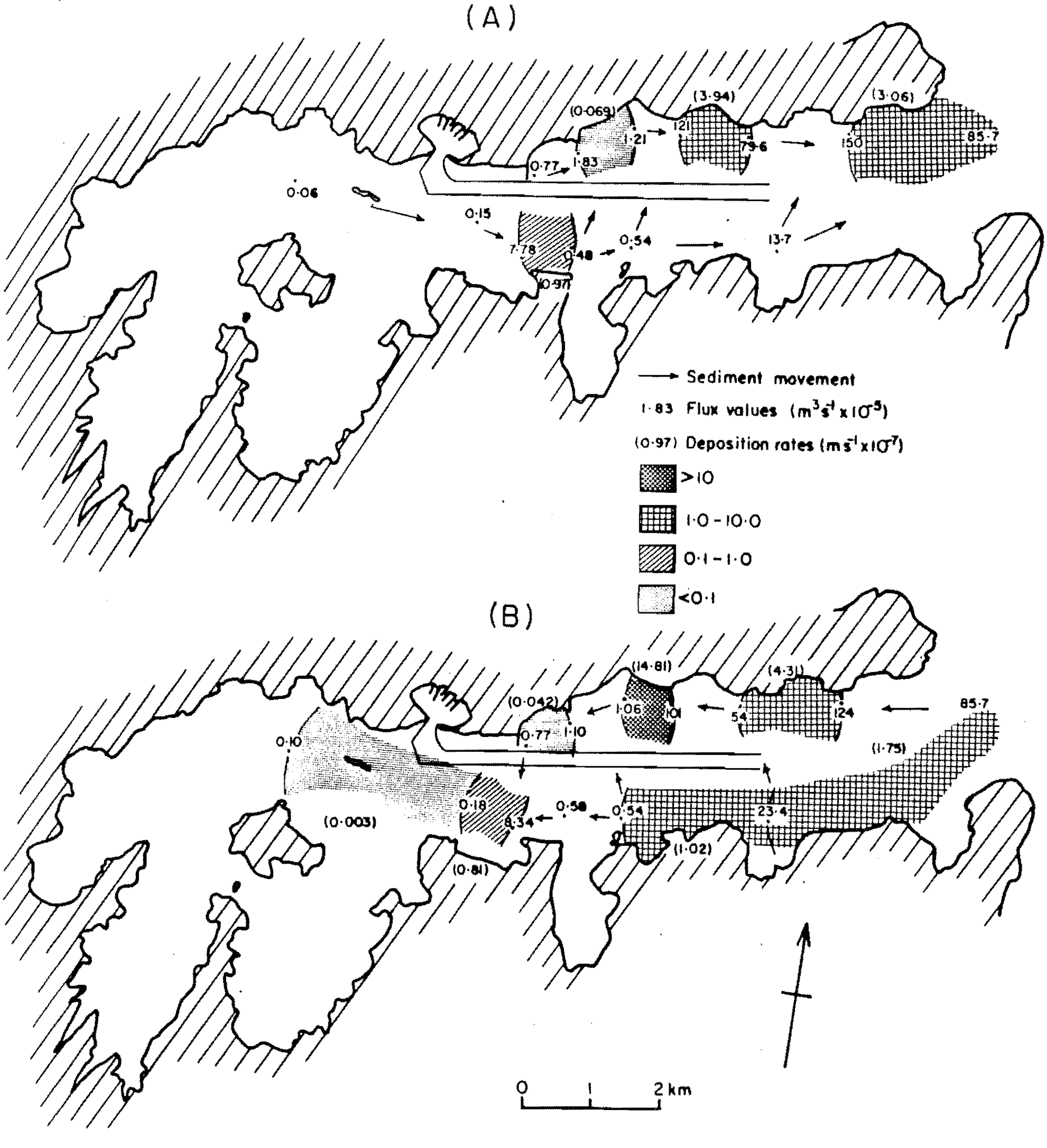


Figure 6.7 Regions of fine grained sediment deposition within the harbour, calculated from flux values and the $(F_1-F_2)/D$ ratio.

A. Ebb tide.
B. Flood tide.

at the harbour entrance, along the northern side, opposite the breakwater, and in the upper harbour. The one area of contra-indication between the two analyses is in Figure 6.7B for the flood tide flux values, which show fine grained deposition between Camp Bay and Purau Bay. This is an area of sandy sediments defined as a scour zone by rollability analysis. A high deposition rate in this region would seem unlikely considering the coarser, sandy nature of bed material found in sediment surveys (refer Figure 3.5), and this suggests that the flux estimation for station 6 may be too high. However, it should also be noted that indicated sediment entrainment and movement on both tides is away from the southern side to the northern side. Long term suspended sediment deposition between Camp Bay and Purau Bay may in fact be less than is implied in Figure 6.7B due to an indicated lateral component of suspended sediment movement.

It should be reiterated here, in agreement with Bokuniewicz (1980), that sediment transported near the bed moves from areas of slower currents to areas of swifter currents. Since it has been established that flux is directly correlated with velocity and sediment supply, it can be demonstrated that near-bed sediment will move from areas of low flux to areas of high flux. Thus a lateral, across harbour transport component has been introduced on both tides, from south to north. Movement will be by currents, and, particularly on the flood tide which has less lateral flow, by advection and diffusion. Thus all fine sediment will tend to move towards areas of high flux on the northern side. Large orders of magnitude differences between flux at stations 10, 11, 12 and the entrance, and flux at other locations within the harbour mean movement to the north by advection and diffusion will be strong. No corresponding return movement will occur as the north to south flux gradient is negative. Effectively the dynamic trap operates as a virtually closed system and fine muds accumulate on the northern side and in the harbour entrance.

In the light of this evidence it is clear that any discussion of the harbour stability cannot merely centre on the entrance hydraulics alone. For Lyttelton Harbour, the "internal stability" is an overriding criterion controlling the entrance 'stability' and the sediment distribution within the harbour. An assessment of harbour stability must therefore take into account the dynamics of the entire harbour, and in this regard existing dredging operations play an important role.

Dredging operations in an otherwise quasi-stable environment upset the established equilibrium and processes have acted to restore it. In this instance both the channel and the spoil mounds represent 'unstable' conditions. Since 1949 spoil has been dumped in the high flux regions of Gollans Bay, and, since 1969, between Gollans Bay and the entrance. As proposed by the dynamic trap model, when transport capacity and sediment load are maximised in a high flux environment the external addition of sediment leads to increased deposition prior to conditions of decreasing velocity being encountered. Figure 6.6 demonstrates this process for Livingston Bay where spoil is dumped. For a given area of high flux the processes will be able to support a maximum level of sediment deposition under conditions of maximum sediment load and transport capacity. Beyond this point any addition of sediment will exceed both the transport and depositional capacity of the area and sediment must disperse under mass movement conditions as a turbidity current. Richards

(1967) examined turbidity currents and noted the observation of a low density turbidity current with a velocity up to 0.61 ms^{-1} on a gradient of only 1 in 2,000. There is also evidence for velocities of 4.5 - 9 ms^{-1} being maintained. Most turbidity currents have their origin in slumps, but some have been correlated with periods of maximum river bedload discharge. Both the dumping of spoil and the dynamic trap principles would probably provide the necessary mechanisms to induce turbidity currents.

Direct evidence that this process occurs is provided in section 3.4.3 (Fig. 3.18A-F) where sounding data show how spoil mounds rapidly achieve a capacity level which is maintained at a stable level. Once this level has been attained the loss rate of spoil dumped at a site is approximately equal to the quantity dumped. The significant correlation between channel siltation in sections 131-145 and tonnage of spoil dumped at Gollans Bay and Livingston Bay (section 5.2.3.2; Fig.5.8B) is inferred here to represent mass movement of spoil by turbidity currents into adjacent channel sections where siltation rates are highest. Deposition rates, established from flux data in Figures 6.7A and B, are highest between Gollans Bay and Livingston Bay indicating that the depositional and transport capacities in this area will be achieved rapidly and maintained. Turbidity currents in this dumping region are therefore likely to occur frequently. Furthermore, high siltation rates in these channel sections will be augmented by the fact that it is the only location where a positive lateral flux gradient is combined with a distinct south to north tidal flow across the channel (Fig. 4.10; section 4.2.2.1).

Excluding spoil transport by mass movement, Figures 6.7A and B indicate that fine sediment will accumulate in the harbour entrance, the only strongly depositional site which has not been utilized as a dumping ground. Heath's (1975) entrance stability model showed the entrance to Lyttelton Harbour to be depositional, which in fact it is. However the correspondence noted by Heath is a totally spurious correlation in the sense that it represents a response to a man-made alteration, and it occurs largely independently of the 'entrance' dynamics. Heath (1976a) later concluded that the harbour entrance was depositional, in terms of his model, because the small littoral drift together with the offshore swell induced a larger stable entrance than would otherwise be associated with tidal control in unconsolidated sediments. In fact, the depositional entrance to the harbour reflects an attempt to establish an 'internal' stability, as part of the process of recycling spoil to the channel. Due to the distribution of flux differentials within the harbour, fine sediment will be deposited on the northern side of the entrance on an ebb tide (see Figure 6.7A) and will move towards White Patch Point, the channel, or the southern side of the entrance on a flood tide. Any material entering the harbour on a flood tide will be deposited on the southern side of the entrance, although it will tend to move towards zones of higher flux on the northern side of the entrance.

Reference to Figure 3.2, showing regions and phases of deposition and scour in the harbour between 1849 and 1976, shows negligible deposition at the entrance between 1849 and 1903. During this period only a minimal quantity of dredging was undertaken. From 1903 to 1951, a period over which channel and berthage dredging operations approached their present levels, deposition at the entrance was considerable reflecting a harbour response to the change in equilibrium caused by the channel and the increased sediment supply in the form of spoil. Entrance deposition was then greatly reduced between 1951 and 1976 despite continuing maintenance dredging at a similar level to that before 1951. At this stage it is postulated that the harbour was approaching a quasi-stable state. High flux zones were at or approaching their depositional capacity so that spoil was recycled with considerable celerity, notably by turbidity currents, and entrance deposition was therefore minimised. It is in this quasi-stable state that the harbour currently exists.

The erosional period between 1849 and 1903, in the centre of the harbour, is presumed to be a response by the harbour to the initial dredging programme. Because the dynamic trap is dependent on both the current flow and the suspended sediment concentration, prior to extensive dumping of spoil within the harbour when near-bed sediment concentrations are likely to have been considerably lower than at present, deposition in terms of the model may not have occurred. If the transport capacity of currents was not exceeded from large supplies of sediment, then the erosional phase of the harbour bed may have seen sediment transported out of the harbour. This cannot readily be confirmed.

It is interesting to note that long-term trends in sediment distribution patterns (Brodie, 1955), and the Lyttelton Harbour Board's dredging records, indicate that siltation in Lyttelton Harbour is insensitive to the location of spoil dumping grounds. As previously mentioned, prior to 1949 spoil dumping within the harbour occurred at Little Port Cooper and Camp Bay, with the exception of reclamation sites. During this period the combined loss rate from both sites was in the order of 800,000 tonnes per annum and entrance deposition and channel siltation continued. While the tidal gyre identified in chapter four would have transported much of this material to either end of the lower harbour, it is likely that considerably more would have moved laterally across the harbour, normal to tidal flow, towards the high flux regions on the northern side. In so doing much would have been recycled to the channel. It must be noted that while flux is dependent on both current velocity and sediment supply, and sediment concentrations would have been high on the southern side during this dumping period, advection and diffusion of fines would still have been from south to north. This is because higher average velocities on the northern side have a greater transport capacity, and wave activity and tidal flow would have dispersed sediment from Camp Bay and Little Port Cooper. Similar current and wave action on the northern side does not disperse sediment in a like manner because the area already exists as a high flux depositional zone which fine material moves into rather than away from.

The above mentioned lateral diffusion process, depicted in Figures 6.7A and B, is important as it explains a characteristic of Lyttelton Harbour which can be accounted for in no other way. The grain size contours are graded laterally across the harbour, and normal to the flow paths. As discussed in chapter three, such patterns are atypical of coastal systems. In this environment the gradation across the harbour from coarser to finer sediments is clearly caused by the diffusion and advection of fines from the southern side to the northern side as a result of the flux differentials. Further, the model provides an explanation for the maintenance of such a sediment distribution, since 1849 (Brodie; 1955), and through times when dredging was either not occurring or spoil was being dumped in locations other than at present.

A final point is worthy of mention in the context of "entrance" stability and its applicability to Lyttelton. The approaches of Bruun (1966; 1978), Heath (1975), and O'Brien (1931) to inlet stability have been to seek empirical relationships between sedimentary and hydraulic processes, at the inlet entrance, which provide a measure of balance. Where the hydraulic processes of scour are able to maintain an open entrance under conditions of depositional littoral drift the inlet is considered to have a 'dynamically stable' entrance. Average velocities through the entrance to Lyttelton Harbour, for average spring tides and for tides of shorter duration, listed in Table 6.3, are sufficient to entrain the fluid muds accumulating there. On average, ebb tides are of shorter duration than flood tides (section 4.2.1.1; Fig. 4.7B) and therefore have higher average velocities. Under conditions of negligible littoral drift, sediment deposition in the entrance would be infrequent using the velocity scour argument. Clearly it does occur though, as a result of flux differentials rather than low current velocities. Listed flux values in Table 6.3 would all result in deposition on the flood tide, and only one would not cause deposition on an ebb tide. In fact the one exception was calculated from an abnormally high spring tide on 27 August 1984, and occurred on a rapid flood tide where velocities averaged 0.36 ms^{-1}. These data, and the flux values presented earlier, demonstrate that the cross-sectional entrance area approach to inlet stability for Lyttelton Harbour is quite irrelevant. Proposed entrance "flushing" concepts will not apply in a situation where stability can be measured in terms of an internal movement and distribution of sediments throughout the entire harbour.

6.5 CONCLUSIONS

Lyttelton Harbour is a structurally controlled tidal inlet with hard rock sides and only one mobile boundary, the bed. It occurs on a non-littoral drift shoreline but deposition has taken place in the entrance at a faster rate than in any other region of the harbour since 1849. The cause is a response to dredging operations which substantially altered a natural state of quasi-equilibrium within the harbour. Restoration of stability required an internal redistribution of sediments, notably dredge spoil, by hydraulics operating within the limits imposed by two solid boundaries. The internal balance being established between harbour hydraulics, bed sediments, and dredging operations has seen the development of distinct zones of erosion and deposition throughout the harbour which are independent of hydraulic processes operating through the entrance.

It has been demonstrated that high concentrations of near-bed suspended sediment will be transported from regions of low flux to regions of high flux, where flux is defined as the rate of transport of sediment. It is a function of both velocity and sediment supply, and as such the highest flux region exists along the northern side of the harbour between Gollans Bay and the entrance. Lowest flux values occur in the upper harbour with intermediate values along the southern side of the lower harbour. The long term trend therefore is for fine grained suspended sediment to be transported towards the northern side of the harbour and the harbour entrance where it accumulates under relatively high velocity conditions by mechanisms proposed in the Dynamic Trap model (section 6.3). Assumptions of the model imply that any area of a given flux value will have a depositional capacity above which the addition of sediment, particularly from spoil dumping, will result in rapid sediment transport away from the area by turbidity currents. This process, and the lateral transport of fine material across the harbour in the direction of positive flux gradients, causes channel siltation and the recycling of spoil.

In the short term most sediment transport will occur in response to a combination of tidal currents, wave activity, and flux gradients. Thus bilateral sand transport will exist on the southern side, suspended sediment in the water column will disperse throughout the harbour, and processes such as the tidal gyre will contribute to spoil recirculation. In the long term however, flux gradients will induce the gradual movement of fine, near-bed suspended material across the harbour from south to north by advection and diffusion. It is concluded that the dynamic trap, in conjunction with other processes operating, provides the major controlling influence for the harbour stability both now and historically. The Dynamic Trap model can be used to account for the following characteristics of Lyttelton Harbour:

(1) The lateral grain size gradation in the lower harbour is due to advection and diffusion of fine material across the harbour.

(2) The insensitivity of siltation in Lyttelton Harbour to the location of spoil dumping grounds within the harbour. Dredge spoil dumped on the southern side is transported back to the channel and to the northern side by wave and current dispersal of the mounds and the subsequent advection and diffusion of particles.

(3) Dredge spoil mounds on the northern side are being maintained at a dynamically stable level which will correspond to the depositional capacity of the location for given flux values.

(4) Channel sections 131-145 have the highest siltation rates as they occur in a region where tidal currents and positive flux gradients combine, and are adjacent to a high flux zone where depositional rates, and therefore turbidity currents, are maximised.

(5) Long term deposition in the lower harbour towards the entrance, and to a lesser extent in the upper harbour, illustrated by comparisons of sounding data between 1849 and 1976.

SEVEN

MANAGEMENT AND SCIENTIFIC APPROACHES TO TIDAL INLETS: AN APPRAISAL WITH RESPECT TO LYTTELTON HARBOUR DYNAMICS

In chapters one and two Lyttelton Harbour was identified as being distinctive from other coastal inlets which have been studied. The main problem associated with explaining how Lyttelton operates was shown in chapter two to be defining what the harbour is, and determining how it is to be regarded as a coastal system. Throughout the foregoing chapters it has also been shown that other types of inlets which are poorly understood, notably well mixed estuaries, may in fact have more in common with Lyttelton Harbour than with the classification of inlets to which they are ascribed.

Chapters three to six have provided a detailed analysis and description of the hydrodynamics and sedimentation in the harbour. The main processes operating within the harbour have been identified and concepts have been developed in chapter six to explain the factors which control the sedimentation and stability of the harbour. It is now appropriate to utilize these data and define what Lyttelton Harbour is and how it is to be regarded as a coastal system. In this exercise it is pertinent to first examine the processes and reasons behind classifications of those inlet types which most closely resemble Lyttelton. This will be done partly to reaffirm those points which differentiate Lyttelton from other inlets, and partly to examine other classifications critically in the light of the findings in this study. It is felt that concepts developed, in chapter six particularly, may be applicable to other types of inlets which are poorly addressed by the literature.

7.1 PROCESSES CLASSIFYING WELL MIXED ESTUARIES

7.1.1 Hydraulic Criteria

It was established in chapter four that Lyttelton is not an estuary, although it could well be placed in Pritchard's (1967a) classification scheme in the category of well mixed estuaries. The main difference between Lyttelton and the classification for a well mixed estuary is that Lyttelton Harbour lacks a pronounced longitudinal salinity gradient. However, much of the harbour is well mixed (refer to section 4.1), and aspects of the dynamics of the harbour are typical of well mixed estuaries, showing similar lateral salinity and circulation patterns. It is apparent then that the terms of reference for an inlet classification need to be defined with care.

In section 2.2 the purpose of scientific classification was outlined. To reiterate, the purpose of classification is to group, and explain the grouping, of like phenomena in terms of the simplest set of basic principles which demonstrate the important similarities between the phenomena and enable them to be grouped as one class or type. The basis of estuarine classification is the salinity structure within an inlet. For stratified and partially mixed estuaries the salinity structure is very significant for the inlet dynamics, being the direct cause of circulation patterns and therefore sedimentation patterns. In essence the salinity structure identifies and explains the main estuarine process; density currents.

However, for well mixed estuaries the salinity structure has virtually no significance at all except to set this type of inlet aside from other types of estuaries. It does not identify the processes operating in an inlet since, by definition, a well mixed estuary cannot have density induced circulation. Non-tidal current velocities measured in well mixed estuaries (Bowden, 1960; Pritchard, 1967a) are substantially less than tidal currents in the same estuaries.

Pritchard (1967a) states:

> It should be borne in mind that the vertically homogeneous estuary may not exist except as a theoretical end member in the estuarine sequence. Present methods of observation may not be adequate in space and time to detect the very slight departure from true vertical homogeneity which may in fact be present in an apparently homogeneous system.

This comment has little relevance beyond a conceptual notion since even if slight departures from vertical homogeneity could be detected, the density effects would have a negligible effect on the dynamics of an inlet. This being so, inlets classified as well mixed estuaries may be more akin to Lyttelton Harbour, which has been shown to be tidally controlled. The notion is examined below where similarities between the dynamics of Lyttelton and the dynamics of estuaries are discussed.

In partially mixed estuaries, stratified flow occurs with a seaward flowing layer on the surface and a landward flowing layer along the bottom (Dyer, 1979; Pritchard, 1967a). Layered flow was found, by dye tracing and current metering, in the least vertically homogeneous region of Lyttelton Harbour, the narrow 'transition' region (section 5.2.2). However, the effect was tidally induced. Flow at all levels was seaward, on an ebb tide, with only slight directional differences indicating the presence of separate layers. In fact the salinity structure is itself tidally controlled in the same region (Fig. 4.2A), with a maximum salinity value in the centre of the harbour, and a declining gradient extending in both seaward and landward directions from this point. The influence of salt advection processes on establishing a bottom, landward flowing current is thus insignificant despite the imperfect vertical mixing.

Horizontal circulation and lateral mixing, characteristic of partially and well mixed estuaries (Dyer, 1977; 1979; Pritchard, 1967a; Wicker, 1965) has been demonstrated in Lyttelton. Dyer (1977) states that "...the dominant terms in the lateral dynamic balance are the water slope, the internal density structure, and the centrifugal force". In Lyttelton the process is tidally dominated and the reversal of horizontal circulations, in the form of a tidal gyre, across ebb and flood tides (section 4.3) again demonstrates that the internal density structure is not important to the processes operating. Fischer (1976) comments:

> Transverse mixing in estuaries is probably caused in part by large-scale horizontal circulations induced by shoreline irregularities and secondary circulations. It may be that... [transverse turbulent mixing] in well mixed estuaries will be found to correlate better against the width and tidal velocity....

Certainly data presented in chapter four demonstrate that currents and circulation in Lyttelton are a function of tidal variability and interaction with the harbour geometry.

A characteristic of effects induced by the geometry and tidal variability is the operation of the harbour as three distinct compartments; the lower harbour, upper harbour, and transition zone between the two. The lower and upper harbours will from here on be termed the inner and outer harbours respectively, to avoid any ambiguity in classifications with the vertical plane which is relevant to density features in estuaries. The harbour divisions are most clearly depicted by the longitudinal salinity structure which shows varying degrees of mixing in the three compartments, and by the complex circulation pattern which forms only in the outer harbour. The division of inlets into several spatial or temporal hydraulic components is not uncommon. Many estuaries alter their 'classification' from well mixed to partially mixed or stratified as a function of longitudinal distance along the estuary (e.g. the Hudson River; Duke, 1961); season of the year (Gironde estuary; Castaing and Allen, 1981); tidal cycles (James River; Haas, 1977), or phase of a tidal cycle (Mersey estuary; Hughes, 1958). With the exception of the first mentioned, all these examples represent temporal components and as such are dissimilar to the Lyttelton example. Separation between well and partially mixed compartments as a function of longitudinal distance is comparable to Lyttelton in that several hydraulic compartments are operating within the same inlet system simultaneously.

Thus some comparability has been established between the hydrodynamics of Lyttelton Harbour and of estuaries, particularly well mixed estuaries. The main apparent difference in classification between Lyttelton Harbour and well mixed estuaries is in the longitudinal salinity gradient. Officer (1977; p.49) states that the important feature for establishing an estuarine circulation pattern is a longitudinal salinity gradient. Such a gradient is not documented as an important criterion in the hydrodynamics of well mixed estuaries which do not possess classical estuarine circulation patterns.

While there is a tidal exchange between the inner and outer harbours in Lyttelton, the two are independent in terms of residual circulations and processes. San Francisco Bay is divided into two regions by Conomos and Peterson (1976), the northern region varying seasonally between a partially mixed and a well mixed estuary, and the southern region being well mixed. They report that tidal mixing occurs between the two regions, with a "permanent estuarine circulation cell" maintained in the northern region near the fluvial input. However, Nelson and Lerseth (1972) (in Fischer, 1976) demonstrated by means of a numerical model that substantial lateral circulation systems operate in both regions. Fischer (1976) regards such residual-transverse circulations as the result of interaction between the tidal wave and harbour bathymetry.

In essence therefore, the interaction between tides and inlet geometry may have a far more profound, long term influence on many estuarine inlets than the more often emphasised density driven processes. Such geometry interaction effects are graphically illustrated in Lyttelton Harbour, particularly with respect to sedimentation. It is notable that in the Gironde estuary, which varies seasonally between well mixed and well stratified, Castaing and Allen (1981) consider that tides play a distinct role in controlling and modulating the transport of suspended sediment in and out of the estuary. This is a contrary viewpoint to classical concepts. They state:

> Most of this research [estuary-shelf interrelationships] has centred on the role of density currents and the mechanisms of flow dispersion in inlets. Although macro-tidal estuarine environments are abundant throughout the world, tidal processes and their specific role in estuary-shelf exchanges of suspended sediment, have been little studied.
>
> (Castaing and Allen; 1981, p.102)

Allen et al. (1980, p.70) observed:

> ...that purely tidal processes appear to be at least as important as density processes in controlling the movement of sediment in macrotidal estuaries. In fact, it appears that purely tidal processes could engender an "estuarine" sediment trap similar to that created by the density circulation.

In macrotidal estuaries such as the Gironde, net seaward sediment transport varies directly with tidal amplitude (Allen and Castaing; 1973). It is suggested here, that while net seaward transport of sediment is not documented for micro or mesotidal well mixed estuaries, the tidal effects proposed for the internal transport and distribution of suspended sediments in Lyttelton Harbour (chapter six) should be considered as a potentially greater process acting on sediments than 'normal' estuarine processes.

7.1.2 Sedimentary Criteria

Sediment transport in tidal inlets occurs in response to wave activity and tidal currents, with net transport resulting from wave oscillatory currents and tidal asymmetry. Tidal asymmetry also induces a net landward transport in estuarine environments by the 'lag' concept (Postma, 1967), discussed in the previous chapter. More generally, suspended sediment transport in estuaries is emphasised to be a function of estuarine circulation and the 'turbidity maximum'. Thus in partially mixed estuaries, surface suspended sediment flows seaward and gradually settles into the bottom flow which transports sediment landward. The turbidity maximum, where suspended sediment is trapped and maximum deposition occurs, is at the convergence between the net landward flowing bottom water in the salinity intrusion, and the net seaward flow in the fresh river water of the upper estuary.

Dyer (1979) applied the same theory to well mixed estuaries following the work of Inglis and Allen (1957) on the Thames estuary, which is generally well mixed (McCave, 1979). Dyer (1979) states that the turbidity maximum alters its position with changes in river discharge. In fact the landward bottom flow may be more a function of tidal flow. Figure 7 in Inglis and Allen (1957) shows the variation in salinity throughout the water column, at a point 50 km inland on the Thames estuary, is a direct function of the tidal cycle, and the same figure suggests that mixing is a function of the phase of the tide. Near bottom landward flow of up to 0.12 ms^{-1} at the same location (Abbott, 1960; Fig.6), is therefore likely to be a function of tidal flow, and accordingly it might be assumed that sediment transport in the Thames will be strongly controlled by tides during periods when the estuary is well mixed. The Thames is a macrotidal estuary similar to the Gironde, both comprising narrow river systems.

Two mesotidal estuaries which are at least in part well mixed are San Francisco Bay and Delaware Bay. Kent (1960) examined diffusion in a scale model of the Delaware River system which is sectionally homogeneous. He found that motion of dye introduced into the estuary was, "a downstream-upstream tidal oscillation upon which the net velocity field imposed a seaward translation". Sediment transport was not investigated. In San Francisco Bay, where the southern region is well mixed, Conomos and Peterson (1976) determined a bidirectional transport process. The northern region, which has near-bed, non-tidal, landward flow estimated at 0.04 ms^{-1}, is an effective sediment trap with sediment being derived from fluvial input and the southern region. Long term data indicate the southern region is experiencing net erosion and sediment loss to the northern reach, although fine grained sediment is simultaneously accumulating in the margins of the southern end. The principal source of suspended sediment in the southern region is from the bay floor, where Conomos and Peterson (1976) report density induced advection processes with non-tidal bottom flow of 0.01 - 0.02 ms^{-1}. In this environment, which also experiences "strong tidal motion" and "large [wind generated] waves", Conomos and Peterson note a high mobility of suspended and surficial sediments, evidenced by the fact that more sediment is dredged annually from channels than is contributed to the bay by rivers.

Odd and Baxter (1980) examined siltation in the Port of Brisbane, which is a microtidal, well mixed estuary. They found that an average 600,000 tonnes of mud enters the estuary annually under river flood conditions at which time the estuary becomes stratified. They observed that "...a large proportion of the total suspended load...is trapped within the estuary by the longitudinal gravitational circulation and is redistributed and deposited in the deep reaches where the bed stresses are low". Their investigation showed that the location and longitudinal distribution of siltation was a function of the flood volume and the artificial geometry of the lower estuary created by dredging. The mechanisms for sediment 'redistribution', and for sediment transport when the estuary is well mixed, were not examined.

The paucity of literature addressing well mixed estuaries means much of the theory relating to their dynamics is no more than speculative. However, considerable similarity can be found between aspects of the examples discussed here and the dynamics of Lyttelton Harbour, and it is therefore worthwhile examining the sedimentation processes in Lyttelton in an estuarine context. Although the examples of the Gironde and Thames estuaries are not entirely applicable to Lyttelton as they are based on rivers without 'harbour' sections, they were included in the discussion to demonstrate the potentially less significant role of density currents in well mixed estuaries.

In all the examples looked at the tidal flows have been demonstrably influential in both the hydrodynamics and sedimentary processes within the estuaries. The most similar example to Lyttelton in terms of structural composition and processes is San Francisco Bay, for which there is the most data. In both inlets there is a considerable quantity of suspended and near-bed sediment being internally transported and redistributed, and both exhibit bidirectional transport systems which tend to separate coarser material from finer material. Coarser sediments are transported up the inlets under wave and tidal currents while fine grained particles are retained and accumulate in marginal regions of the well mixed, outer harbours. No conclusive or specific mechanisms for sediment transport in well mixed estuaries have been provided in the literature, so it is postulated here that the Dynamic Trap model, proposed in chapter six for the deposition of fine sediment in Lyttelton, is equally applicable to well mixed estuaries. One can draw an analogy between San Francisco Bay and Lyttelton Harbour in that both operate as two largely distinct sections. In the former case the inner harbour, often partially mixed, portrays a turbidity maximum which traps sediment, while the outer, well mixed harbour exhibits independent sedimentary characteristics. In Lyttelton, while there is no longitudinal salinity gradient or turbidity maximum revealed on the low tide salinity profiles (Figs. 4.1, 4.2 and 4.3), the inner harbour does accumulate sediment on tidal flats which coincide with the region of maximum freshwater input (Chapter three). Similarly the outer harbour operates independently in terms of sedimentary mechanisms. Studies of "well mixed estuaries" have tended to concentrate on mechanisms operating in those portions of the estuary which are not well mixed, and processes in the remaining portions are frequently ignored, implied, or only briefly assessed.

It seems likely that the Dynamic Trap model is applicable to a wide range of inlet situations. As illustrated in Lyttelton Harbour, it can cause sediment to be trapped within an inlet and may induce an 'estuarine trap' situation such as the accumulation of fine material at the entrance to the narrow transition zone opposite the Lyttelton breakwater (section 6.4). Einstein, Asce and Krone (1961) noted fine sediment accumulating in deeper channel areas in San Francisco Bay, predominantly during periods of low fluvial sediment input. The sediment originated from the bay floor and was transported by local currents, but it was observed that the speed of scour was reduced with increasing concentration of the flowing water. Einstein et al. (1961) felt this "indicated a type of equilibrium condition to be approached between scour and deposition", although no attempt was made to define the equilibrium. The dynamic trap provides an explanation for such an equilibrium in that sediment moves towards areas of greater flux, with scour decreasing as flux, or the transport capacity, is maximised, and deposition increasing as a result of small changes in local current velocities inducing large flux changes, or negative flux gradients.

7.2 TIDAL INLET CLASSIFICATION

The previous two sections have examined concepts relating primarily to well mixed estuaries in relation to the dynamics of Lyttelton, and little has been said regarding non-estuarine tidal inlets. Aspects of these are discussed below with respect to this study.

Bruun (1978; p.1) defines a tidal inlet in terms of four sections:

> They are the Gorge Channel, that means the section with minimum cross sectional area usually with relatively little wave action, the Bay Section with its shoals and channels, and the Ocean Section which may include shoals or bars and one or more channels. Wave action plays an important role in the development of the ocean section. Finally there is the Intermediate Section between the ocean section and the gorge where currents and wave combine.

Most tidal inlets studied probably conform to this description, reflecting a quasi-equilibrium balance between wave and current processes and the sedimentary inlet boundaries. Lyttelton is subject to both wave and current processes but these are unable to develop the 'Bruun sections' because of the structural immobility of the harbour walls. Thus Lyttelton is essentially a single section, combining all four sections into one. This is particularly so for the outer harbour which is subject to current and wave activity in its entirety.

The transition zone between outer and inner harbours most closely resembles a gorge section in its form as the narrowest cross section, although it cannot be regarded as the gorge for the entire harbour because the hydraulic radius is less than that of the harbour entrance (FitzGerald and FitzGerald, 1977). However, it might be regarded as a gorge to the inner harbour, with the outer harbour representing the ocean and intermediate sections. It has already been established that the transition region comprises a form of boundary separating the hydraulic and sedimentary processes of inner and outer harbours in a manner which could be applied to the Bruun type of gorge theory. To apply the concept in this manner may appear somewhat inappropriate, but it serves to emphasise a valid and important point when considering the context of the classification of Lyttelton. For inlets on littoral drift shorelines, both the hydraulic processes, and sediments are largely externally derived, so that the inlets may be defined in terms of their entrances, processes and sediment which enters the entrance, and adjustments which are made to cater for entrance variations. In the case of Lyttelton where sediments are largely internally derived, and wave and current processes entering the harbour become confined between the walls and modified by geometry, it is more relevant to define the inlet in terms of processes operating <u>within</u> the inlet itself rather than through the entrance. For example, the internal redistribution of sediment is more important in

Lyttelton than its accumulation or erosion within the entrance *per se*.

7.2.1 Classification of Lyttelton Harbour

An attempt has been made in the foregoing discussion to establish a fundamental difference between Lyttelton Harbour and inlets generally examined in the literature, and at the same time to demonstrate the potential applicability of concepts derived from the present study to other forms of inlets, or parts of inlets. No existing classification can adequately describe Lyttelton, particularly its dynamics and the mechanisms which operate within it.

The primary factor which differentiates Lyttelton Harbour from the well mixed estuary classification is the longitudinal salinity gradient in well mixed estuaries. However, because of the pronounced tidal mixing, the longitudinal salinity gradient criterion has little relevance to the hydraulic and sedimentary processes which operate within well mixed estuaries. Thus a definition is required which will adequately describe and categorise Lyttelton Harbour in terms of its processes, and which will also be applicable to other types of inlets with like characteristics. It is desirable that a researcher can approach an inlet in terms of the processes which operate within it and control it. The following definition is proposed for Lyttelton Harbour:

> An elongated, structurally controlled tidal inlet with only one mobile boundary and predominantly tidal processes.

The term 'elongated' is necessary as it excludes bays and embayments. However, the important phrase in this definition is that it is 'structurally controlled', referring to the rock walls and the strict limits they impose on processes within the inlet. A developed state of quasi-equilibrium in many littoral drift tidal inlets, or river mouth estuaries, reflects the ability of such inlets to alter their planform and the location and size of their channels, in response to changes in local hydrology and sedimentary conditions. Lateral movement of channels is important for achieving equilibrium. As Bruun (1978) notes, it is a well known phenomenon that tidal inlets tend to "place" themselves in front of shoreward indentations in the depth contours. He observes that, "the development [of the inlet system] depends highly upon the entrance configuration and its relation to flow and material transport from all sides".

Given that well mixed estuaries can be regarded as tidal inlets in terms of their processes, two sub-categories can be identified. Those which exist in unconsolidated boundaries are one category, and will probably conform to Bruun type relationships, while those which are formed in solid boundaries are another category and will conform to the types of processes and relationships which occur in Lyttelton Harbour. This type of inlet can be termed a "structurally controlled tidal inlet". The term 'tidal' is important as it excludes solid boundary inlets such as fjords, while other types of inlets such as rias may or may not be included depending on their boundary characteristics or level of estuarine development.

The structural controls imposed in Lyttelton exclude the possibility of changes in channel configuration or orientation, and the hydrodynamics of the harbour are necessarily determined by the external orientation of flow into the harbour entrance, and the internal flow which is a function of harbour geometry. Thus both sedimentary and hydraulic processes are "controlled" laterally within Lyttelton, and the harbour bed is the only boundary on which "equilibrium changes" can be imposed. While the inner harbour contains tidal flats, and as such possesses a degree of lateral flexibility, responses in this area would be unlikely to occur on a large scale, independently of the dynamics in the remainder of the harbour. Therefore the 'structural control' concept can be applied to the harbour as a whole.

With the proposed definition in mind it is worthwhile examining several other inlet examples. In his paper on inlet stability, Heath (1975) found that four of 20 inlets examined failed to comply with the tidal prism, cross-sectional area relationship derived. All fell on the 'depositional' side of the function (see section 6.1), and all were structurally controlled, with rock boundaries. Three, Lyttelton, Akaroa, and Wellington Harbours, were closely clustered together on Heath's graph, while the fourth, Paterson Inlet which has a complex entrance constricted with islands, differed substantially from the derived function. Akaroa and Wellington Harbours are examined briefly below in relation to the Lyttelton Harbour dynamics and the proposed definition for Lyttelton.

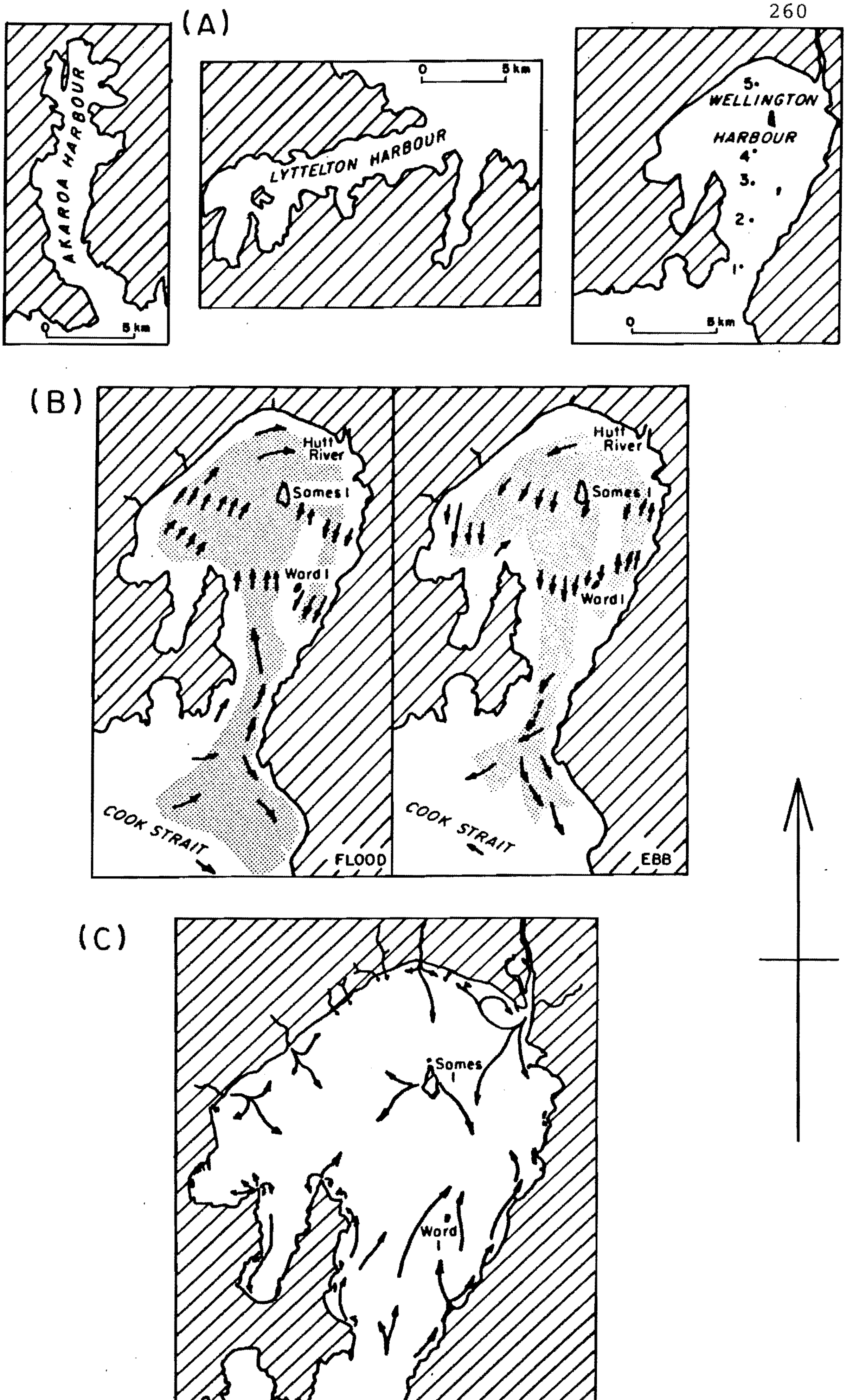
Figure 7.1A shows the geometries and comparative sizes of the three harbours. All possess a single wide entrance and are somewhat rectangular in shape. It should be noted that all three harbours are entirely rock walled with minimal areas of tidal flats, and the entrance regions are unconstricted. Other harbours of similar size and shape which complied with Heath's relationship (e.g. Otago and Whangarei) contain

Figure 7.1 Geometry and circulation characteristics of two other rock-walled inlets: Wellington and Akaroa Harbours.

A. A comparison of inlet geometries.

B. Circulation of tidal currents in Wellington Harbour. After Brodie (1958).

C. Sediment transport directions in Wellington Harbour. After Van der Linden (1966).


(A)
AKAROA HARBOUR
0
5 km
LYTTELTON HARBOUR
0
5 km
WELLINGTON HARBOUR
5.
4.
3.
2.
1.
0
5 km
(B)
Hutt River
Somes I
Ward I
COOK STRAIT
FLOOD
Hutt River
Somes I
Ward I
COOK STRAIT
EBB
(C)
Somes I
Ward I

unconsolidated spits at the entrance which alter the controlling hydraulic factors. The influence of the rock walls on the internal dynamics of these three harbours is thus presumed to be the cause of their failure to fit the entrance area model.

Akaroa Harbour has no major stream input and is therefore presumed to be tidally dominated, although no data are available to this effect. However, Wellington has a major fluvial input from the Hutt River which has a daily discharge of 2.6 - 180 x $10^6 m^3$ (Booth, 1975), and a mean discharge of 30-2083 $m^3 s^{-1}$. The normal salinity range is 33.5 - 34.5^o/oo, but in winter the Hutt River discharge affects surface salinity to a depth of less than 5 m, for about half the harbour width, decreasing salinity values to around 21^o/oo (Booth, 1975). Despite this, the harbour is dominated by tidal processes and has efficient tidal mixing (Booth, 1975; Heath, 1977; Maxwell, 1956). Brodie (1958) examined circulation patterns in Wellington Harbour and determined clockwise and anticlockwise circulations within the harbour for flood and ebb tides respectively. No reference is made by any author to the presence of estuarine circulation patterns.

Figure 7.1B shows the circulation patterns established by Brodie, and it can be seen that they closely resemble circulation patterns in Lyttelton Harbour (see Figure 4.19). The influence drawn here is that tidal flow in Wellington is controlled in a similar fashion to that in Lyttelton, by the solid boundary limits to the harbour. Booth (1975) and Maxwell (1956) both consider that the normal discharge of the Hutt River is insufficient to materially upset the hydrological regime of the harbour. Thus circulation results from tidal interaction with the harbour geometry.

Further, it is interesting to note the directions of sediment movement within the harbour and through the entrance. Again similar to Lyttelton, sediment is trapped within Wellington Harbour. Transport is northward away from the entrance, although tidal currents are too weak to instigate transport as a general rule (Carter, 1977). Van der Linden (1966) established that most sediments were fine grained silts and clays, poorly sorted, with the Hutt River being the main sediment source. Silts and clays covered the central area of the harbour, with coarser, better sorted material in the entrance. Figure 7.1C illustrates transport directions inferred from textural parameters by Van der Linden showing a bidirectional transport system. Carter (1977) states that sand accumulates mostly at the northern limits of the harbour away from the central region of silt and clay. This suggests that particles of differing grain size are hydraulically separated within the harbour and, broadly speaking, deposited in different locations as a function of different transport and depositional mechanisms. In this matter, Carter's findings are somewhat contrary to Van der Linden's inferred transport directions, and it is in such a situation that the Dynamic Trap concept may be most applicable.

A final point is worthy of note. Heath (1975) argued that the entrances to the four 'deviating' harbours were depositional. In fact Van der Linden (1966) describes the entrance bed in Wellington Harbour as a winnowed deposit, and Carter (1977) has shown transport to be away from the entrance. The entrance to Lyttelton has been shown to be depositional, but for reasons totally unrelated to Heath's inlet model (Chapter Six).

It is apparent that such rock-walled inlets operate in a very different manner to littoral drift inlets or estuaries, but demonstrably contain similar process characteristics which are not readily explained by traditional concepts. Bowden (1967) states:

> A comparison of data obtained from a number of estuaries leads to a...classification of estuaries based on the physical conditions in them. A logical development is the derivation of general principles, so that when an estuary not previously studied is encountered one may be in a position to predict the circulation and diffusion in it from a limited number of parameters.

Following this approach, the definition applied to Lyttelton at the beginning of this section is proposed in a more general context to rock-walled inlets which are not controlled by estuarine processes. In this respect the definition should also be applied to rock-walled inlets generally described as well mixed estuaries. Here the phrase, "with predominantly tidal processes", is important to the definition, and classification. Well mixed estuaries represent an end point to a classification sequence (Pritchard, 1967a) and are little understood. It is postulated here that tidal processes predominate in such inlets in terms of mixing, circulation, and transport, and this point has been argued earlier in the chapter. It therefore seems more appropriate to define these inlets in terms of the dominant processes operating, both from a management and a scientific point of view. The Lyttelton Harbour definition is proposed, as one which identifies not only the dominant processes, but also the limits and controls imposed on those processes and the potential regions in which the inlet can respond to internal and external changes in the overall system. Following Bowden's (1967) observation, a number of parameters are listed in section 7.3.1 from which aspects of the harbour dynamics can be predicted for this type of inlet.

7.3 DISCUSSION: APPROACHES TO STRUCTURALLY CONTROLLED INLETS

Having classified Lyttelton Harbour, the broader issues in the structural control concept will now be examined. The most significant difference determined from this study between Lyttelton and inlets generally discussed in the literature, is in the processes and mechanics of sedimentation within the harbour. The emphasis in this type of inlet on internal redistribution of sediments, rather than entrance dynamics, has already been discussed, but the implications of this in management and scientific terms require further evaluation.

An additional difference between Lyttelton and many tidal inlets is the sediment size. Bruun (1978) does not address the complexities of sediment transport or stability for inlets with fine grained sediments, and for most estuarine studies fine grained sediment movements are merely attributed to estuarine circulation patterns. Thus management of fine grained inlets requires further evaluation. In many cases, as with Lyttelton, the maintenance of a navigable channel by dredging is the main concern, and associated problems with this are closely tied to sedimentation mechanics and inlet stability. The derivation of general principles applicable to structurally controlled inlets would prove useful to a general understanding of their dynamics, and for maintaining cost effective operations in any commercial harbour.

7.3.1 General Principles Pertaining To Tidal Inlets

General principles can be applied to both hydraulic and sedimentary processes in a variety of contexts. Within the context of this study, two related phenomena, which reflect many aspects of overall inlet dynamics, will be evaluated further here. They are stability and dredging operations.

The traditional approach to inlet stability which examines entrance criteria (Bruun, 1978; Heath, 1975; O'Brien, 1931, 1969) has been shown to be inappropriate for harbours such as Lyttelton. Similarly it would appear to be equally inappropriate for many inlets, structurally controlled or otherwise (Nielsen and Gordon, 1980; Byrne et al, 1980). Other stability studies have expanded the number of analytical criteria to include the tidal amplitude and period, basin surface area, friction factors, and hydraulic radius of the entrance channel (Escoffier, 1940; Nielsen and Gordon, 1980; O'Brien, 1980; O'Brien and Dean, 1972). However, emphasis is still placed on the entrance as the controlling structure. Given that in many inlets, and most New Zealand harbours, a navigation channel is dredged not only through the entrance but also along a major portion of the inlet length, equilibrium is disturbed throughout the inlet, albeit by artificial means. Therefore consideration of stability at the entrance to an inlet is unlikely to reflect the response of the inlet to internal changes in equilibrium. The entrance hydraulics and stability, expressed as an entrance area/tidal prism relationship, are less likely to influence inlet stability in a structurally controlled inlet than are the internal dynamics.

In this respect, three harbours evaluated by Heath (1975), Otago, Lyttelton, and Wellington, show varying characteristics. The latter two were both classed as having depositional entrances by Heath. Of these it was found that Lyttelton, which has an extensive dredged channel, was depositional at the entrance, while Wellington which is not extensively dredged was not depositional. Alternatively Otago, which was determined to have a stable entrance, has a dredged channel of considerable length and, like Lyttelton, is depositional within the harbour inside the entrance (Kirk, 1980). Thus entrance stability in structurally controlled inlets may in fact be influenced more by internal stability factors than by the apparent entrance dynamics. The term 'apparent dynamics' is used because hydraulic characteristics are frequently calculated from the same empirical relationships which are used in the entrance area/ tidal prism calculations of stability.

An approach to the question of stability must therefore incorporate both scale and sedimentary mechanics criteria. The scale criterion is readily illustrated by Lyttelton Harbour which operates as several discrete compartments, none of which can be investigated singly to analyse long term stability. As has been shown in chápter six, entrance characteristics are not the sole cause of internal stability within Lyttelton. It is the combined dynamics of the inner harbour and the north and south sides of the outer harbour which cause existing patterns of sediment movement, and therefore stability. Entrance deposition is a function of the internal sediment redistribution, and existing stability characteristics are largely a function of the dredging operations which initially altered the equilibrium, and provided a large sediment supply for the system to work with. Analysis of 'stability' characteristics in any single compartment by investigation of the hydraulics in that compartment would be likely to provide spurious results, failing to account for processes in the remainder of the harbour influencing the overall pattern of sediment distribution.

The examples of Otago, Wellington, and Lyttelton Harbours examined here have all been structurally controlled. However, the scale of approach is presumably equally applicable to all inlets, in that sedimentation and circulation patterns within the inlet will influence entrance characteristics and vice versa. This 'internal' study of dynamics and sedimentation has been largely ignored in stability studies by Bruun (1978), O'Brien (1931) and others in their concern for inlets on unconsolidated littoral drift shores.

Crickmore's (1968) statement that, "apart from the natural rock basin harbours, most ports are sited in areas that are in a state of dynamic equilibrium, as far as sediment is concerned", carries the inference that rock basin harbours do not achieve dynamic equilibrium. Such a premise can only be based on the assumption that two or three mobile boundaries are required for dynamic stability to be maintained, but is ill founded as illustrated by the present study. The argument that a dredged channel creates an imbalance which the system will act to restore is not necessarily precise. Smith (1976) found that a channel dredged in San Diego Bay, a well mixed estuary, remained with virtually no maintenance dredging being required. The bay had a minimal natural sediment input and spoil was utilized for reclamation making it unavailable for recycling. Reclamation projects altered both the geometry of the bay and the tidal prism, affecting the hydraulic regime which in turn would affect sedimentation processes operating within the estuary (Smith, 1976). However, the absence of an available sediment supply, with the exception of the bay floor, must be noted as a plausible reason for low channel siltation rates in San Diego Bay. Shideler (1975) pointed out that modern sedimentation patterns within an estuary "...represent composite responses to a complex combination of physical, chemical, and biological processes that are regulated by the bay's hydraulic regime and geologic framework". Within the notion of a geologic framework, the magnitude of sediment supply to the system should be included. Lyttelton Harbour provides an excellent example to develop this concept further.

Chapters five and six demonstrated that the major source of sediment causing channel siltation in Lyttelton was from recirculated dredge spoil dumped within the harbour. Considering the comparatively insignificant, natural input of sediment (section 3.4), in relation to quantities dredged, it is postulated here that siltation rates would be substantially reduced if spoil was unavailable for recycling; for example if it was dumped at sea. Thus the "imbalance" would be rectified at a markedly slower rate, and a situation similar to San Diego Bay would exist where maintenance dredging was minimal. This is particularly applicable to structurally controlled inlets where an 'altered' hydraulic system cannot obtain sediment from the inlet perimeter. The main potential sediment source is therefore the bed, and it has already been shown that the bed response in such inlets does not necessarily conform to traditional hydraulic/stability theory, as in the case of 'entrance stability' (Chapter Six).

Consideration of the Dynamic Trap theory (section 6.3) shows the relationship between sedimentation rates in Lyttelton and the sediment supply. Fine grained sediment moves from areas of lesser sediment flux to areas of greater sediment flux, and deposition occurs when the transport load capacity of the flow at a given site is exceeded. However, if the sediment supply is greatly reduced, transport load capacities will be exceeded less frequently and deposition will be less. The association may appear logical, but it must be emphasised that in this context the inlet system is dependent on the sediment supply to restore equilibrium when it is theoretically lost. The hydraulic processes in a structurally controlled inlet cannot acquire a sediment supply, if one does not exist naturally, as readily as in inlets which have mobile, and erodable perimeters.

Sedimentation patterns within Lyttelton therefore represent a combination of sediment supply and hydraulic processes which are regulated by the harbour geometry, and controlled within the limitations imposed by the rock boundaries. Given this criterion for inlet control by geometry and boundary conditions, an attempt was made to derive a general principle pertaining to sedimentation patterns in structurally controlled inlets.

In section 6.3 it was shown that small variations in flow velocities between two locations could induce substantial suspended sediment deposition as a result of flux gradient variations. It is argued here that such flow variations may reflect changes in harbour widths from place to place. The relative mean velocity at any given location within the harbour will in part be a function of the distance into the harbour at that location, reflecting change in power in the tidal wave as it flows along the length of the harbour. These two factors have been combined in a dimensionless coefficient, D_E/W, to express sedimentation at any location within structurally controlled inlets. D_E represents the distance between the harbour entrance and a given location, and W is the harbour width at the same location. Values for the coefficient for the 12 current stations in Lyttelton Harbour are listed in Table 7.1A.

Figure 7.2 shows graphs of sediment flux at the 12 current stations against the dimensionless coefficient D_E/W, for ebb and flood tides. Regression lines have been fitted to the plots with an r^2 value of 0.62 in both cases, which is statistically significant at the 0.01 confidence limit for 12 points (Mills, 1955). The correlations are negative, such that flux increases as D_E/W decreases.

Considering the potential error involved in the calculation of flux values at each current station (discussed in section 6.2.1) the regression fit is extremely good and of considerable significance. Since the correlation is derived from a very limited data set, it can only be proposed tentatively as a concept applicable to the structurally controlled inlet classification. Further evaluation of the relationship is obviously required. However, as a working hypothesis it has two important applications for structurally controlled inlets, based on the Dynamic Trap model proposed in chapter six.

Table 7.1 Entrance Distance/Width ratios for
(A) Lyttelton Harbour current stations, and
(B) Wellington Harbour.

(A) Station No.	Distance[1] D_E (m)	Harbour Width (m)	Distance/ Width Ratio	(B) Wellington Harbour Site No.[2]	D_E/W Ratio
1	8000	1550	5.1613	1	1.1669
2	7825	1625	4.8154	2	1.1481
3	7200	1950	3.6923	3	1.2222
4	6425	1975	3.2532	4	0.9032
5	5600	2425	2.3093	5	2.1051
6	3500	2625	1.3333		
7	6875	1750	3.9286		
8	6225	1975	3.1519		
9	5375	2425	2.2165		
10	4650	2125	2.1882		
11	3675	1900	1.9342		
12	2020	2050	0.9854		

1. Distance between current station and harbour entrance

2. Site numbers to which ratios apply shown in Figure 7.1A

1. Transport directions of fine grained sediment can be predicted from harbour geometry using the D_E/W ratio, given that fine sediments move from regions of low flux to regions of high flux.
2. Regions of high siltation rates may be identified within the harbour for fine grained sediments, given that a positive or negative flux gradient between two points may be inferred from the D_E/W ratio.

These applications are very general in this form. In Lyttelton the relationship fails to separate depositional rates that are substantially different on the northern and southern sides of the outer harbour, and this is reflected in the regression plot in Figure 7.2. The D_E/W, flux relationship in the central regions of the harbour is very broad, so that a value of D_E/W of around 2 may correlate with several flux values which are an order of magnitude apart. However, at either end of the relationship, when D_E/W is at a maximum or minimum, the correlation between D_E/W and the flux is much closer and the data points are less scattered. The maximum and minimum values of D_E/W correspond to the head and entrance of Lyttelton respectively, and in these two locations the depositional rates on either side of the harbour are more uniform. Thus the pattern of the plotted data in Figure 7.2 may be as significant as the regression line, and may relate to the geometry or circulation within the harbour. More data would be required to verify this hypothesis.

Few data exist for other tidal inlets to which the coefficient could be applied and evaluated. In a limited fashion it was applied to Wellington Harbour, although no depositional rates or current data were available. Five

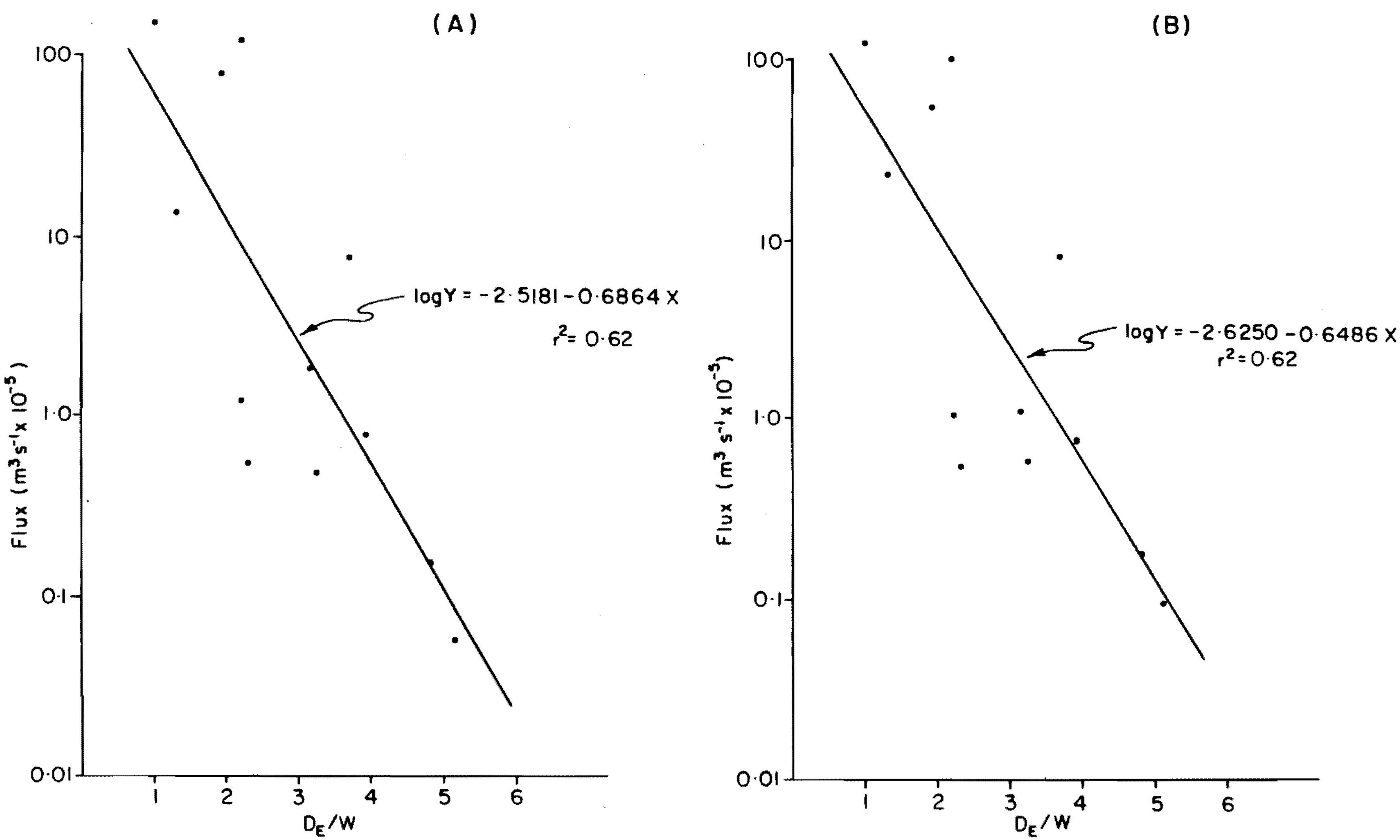


Figure 7.2 Scattergrams of flux values vs the dimensionless D_E/W coefficient for Lyttelton Harbour.
A. Ebb tide.
B. Flood tide.

sites are shown in Figure 7.1A for which D_E/W values are listed in Table 7.1B. From these figures one would expect transport of fine grained sediment into the centre of the harbour, and maximum deposition of fines to occur at site 4, relative to the other sites. This prediction is in agreement with data compiled by Carter (1977) and Van der Linden (1966), who show that transport is towards the harbour centre, and that the predominant accumulation of fines is also in the central harbour region (see Figure 7.1C).

The interesting point regarding the D_E/W ratio in Wellington Harbour is that the pattern of the values with respect to the form of the harbour is different to that of Lyttelton. While the maximum D_E/W value in Wellington occurs at the head of the harbour, the minimum value is in the centre rather than at the entrance. Consideration of Figure 7.1 shows that the geometry of Wellington is significantly different to that of Lyttelton and Akaroa harbours. However, the minimum D_E/W value occurs at site 4, within the circulatory gyre (Fig. 7.1B) which operates in the harbour. The minimum D_E/W value in Lyttelton is also within a gyre, the difference between the two harbours being that the gyre operates in the outer harbour as far as the entrance in Lyttelton, but operates away from the entrance in Wellington Harbour. Therefore, while the D_E/W pattern differs in terms of the location within the two harbours, it may in fact be quite similar in terms of the hydraulics and circulation within the harbours.

No data is available to enable the above comparisons for Akaroa Harbour. However, given that it is closely grouped with Lyttelton and Wellington in Heath's (1975) entrance area/

tidal prism model, it seems more than likely that its rock boundaries and similar geometry to Lyttelton will give it similar hydraulic controls and probably a similar D_E/W pattern to Lyttelton and Wellington.

On the basis of the above, and foregoing arguments, the following parameters need to be considered when 'predicting' sedimentation patterns in structurally controlled tidal inlets:

(1) The D_E/W ratio for a number of sites within the harbour.

(2) The harbour geometry.

(3) Bed sediment grain size (the D_E/W ratio and Dynamic Trap models have been proposed for fine grained silts and clays).

(4) The presence of unconsolidated features at the harbour entrance (e.g. the spit at the entrance to Otago Harbour).

(5) The magnitude of the sediment supply to the harbour and the form it is in (e.g. bedload or fine grained suspended material).

7.4 CONCLUSIONS

The main point to be drawn from this chapter is the identification and definition of Lyttelton Harbour as a tidal inlet which operates in a manner which is fundamentally different to inlets hitherto discussed in the literature. The fundamental difference exists in that the harbour hydraulic and sedimentary processes are controlled internally within the boundaries imposed by the solid walls and geometry. This phenomenon delineates the harbour dynamic characteristics from those of littoral drift tidal inlets, while the absence of typically estuarine processes distinguishes the harbour from estuaries. Hydraulic processes are derived primarily from tidal currents, and it has been demonstrated that sedimentary processes within the inlet are largely a response to the interaction of the tidal wave with the geometry of the rigid harbour perimeter. This interaction can be characterized in the form of a dimensionless coefficient which expresses the sediment flux at any given location within the harbour as a function of the lateral and longitudinal harbour dimensions at that location.

It is proposed that the concept of structural and geometrical control of inlet dynamics is relevant to any inlet where the dominant hydraulic process is the tide, and the bed is the only mobile boundary. In this respect many so-called well mixed estuaries, where the tide is dominant over estuarine processes, might well be redefined as "structurally controlled tidal inlets". This classification is important and needs to be applied since the approach to understanding and dealing with this type of coastal inlet is fundamentally different to other forms of inlets.

EIGHT

CONCLUSIONS

In chapter one a number of interesting characteristics and problems associated with sedimentation in Lyttelton Harbour were identified. For example, the lateral gradation of sediment grain size contours within the harbour, the insensitivity of channel siltation to the location of spoil dumping grounds, and the long term and contemporary harbour stability in spite of a massive dredging programme. For the purposes of research, these aspects of the sedimentary mechanics in the harbour were focussed in three questions:

(1) What factors controlled harbour stability under natural conditions, in an inlet possessing only one mobile boundary which can be subjected to alteration to achieve stability?

(2) In what manner did the harbour respond to substantial changes to the system, from the dredging of the channel, which upset the equilibrium?

(3) What factors currently control harbour stability under the new conditions, with the channel dredged and spoil dumped within the harbour?

The aims were to answer these questions through a detailed study of the sedimentation and hydrography of the harbour in which the following factors were to be determined:

(a) The sources of sediment supply to the harbour and the relative contributions of these sources to harbour sedimentation.

(b) Rates of harbour sedimentation and channel siltation, and the immediate sources of sediment supplied to the channel.

(c) The nature of circulation patterns within the harbour and the driving forces behind them.

(d) The hydraulic processes inducing sediment erosion, transport, and deposition and the mechanics involved in sediment transport around the harbour.

(e) The effects of internal sedimentation patterns on harbour stability.

(f) Dredge spoil dispersal patterns and the effects of dredging operations on the harbour dynamics and stability.

(g) The effects of a hard rock geometry on circulation and sedimentation patterns and on harbour stability.

The principal findings of the study fall into three broad areas, one specific to Lyttelton Harbour and of use mainly for local and applied purposes, and two areas of more general significance in inlet studies and dynamic geomorphology.

The first area, specific to Lyttelton Harbour, concerns the nature of sedimentation and processes within the harbour. It has been shown that the harbour operates as several relatively discrete compartments in both sedimentary and hydraulic terms. The harbour can be divided in two along the longitudinal axis, with fine muddy sediments on the northern side and coarser, sandier sediments on the southern side. It can be further divided longitudinally into an inner harbour, comprising the area west of the port, and an outer harbour which is the area east of the port and breakwater. Between these two areas is a 'transition' zone which effectively separates the inner and outer harbours, and is the least well mixed region in Lyttelton. The inner and outer harbours are predominantly well mixed regions. These harbour divisions result primarily from the interaction between the hydraulic processes and the harbour geometry.

Tidally driven currents are the main hydraulic processes in Lyttelton, and are notable for their variability, and the extent to which they are influenced by external, non-tidal factors. The duration of both flood and ebb tides varies between 5.0 and approximately 8.25 hours, with the flood tides being slightly longer on average. The primary driving force behind the tides is the principal lunar constituent M_2, but the variability in tidal duration is strongly influenced by weather patterns and continental shelf edge wave oscillations. The weather influences are part of the 5-10 day weather cycle in New Zealand, and comprise southwesterly and northeasterly airflow along the east coast of the South Island. Southwesterly flow augments the flood tide, which sets from south to north, while the northeasterly flow augments the ebb tide.

Continental shelf edge waves occur along the east coast of New Zealand north of Banks Peninsula, and these generate oscillations in Lyttelton with a period of 2.5 to 3.5 hours. The oscillations are significant and can be seen as protuberances of the water level curve at the tide gauge. Both weather patterns and edge wave oscillations have a strong influence on the tides, comparable to the effects of the K_1 tidal constituent or the M_f constituent which produces the spring-neap, fortnightly cycle.

Mean current velocities are 0.23 and 0.22 ms^{-1} for flood and ebb flows respectively, with little difference evident between spring and neap tide velocities. The tides flood more strongly on the southern side of the harbour, and ebb predominantly on the northern side, so that a clockwise circulation pattern exists within the harbour. Density gradients are non-existent and circulation can be regarded as two dimensional in the horizontal plane.

In the outer harbour, the interaction between the harbour geometry and tidal currents induces a gyre which operates for up to 50% of a given tidal cycle. The duration is a function of tidal variability (the length of a tide), and it is inferred also to be a function of a critical current velocity which is probably associated with the tide length. Thus the gyre will sometimes operate for only short periods, or fail to develop, or only partially develop. On flood tides it rotates in a clockwise direction and in an anticlockwise direction on ebb tides.

The wave environment at Lyttelton is mixed, combining ocean swell and locally generated wind waves. Dominant wave conditions consist of long period, 20 second waves which occur 30% of the time, and 12 second waves which occur 24% of the time. However, in terms of sediment transport, the most effective waves are 11 second storm waves. These conditions occur only 10% of the time but the waves are steeper and have a higher significant wave height than other wave conditions. Storm waves effect rapid sediment transport, and 11 second waves are an order of magnitude more effective at inducing transport than other wave conditions, despite their low frequency of occurrence.

Ocean waves and swell regularly penetrate the harbour as far as the port, and infrequently penetrate beyond the port into the inner harbour. Swell entering the harbour approaches from the ENE so that it travels directly along the longitudinal line of the harbour. Refraction results primarily from the influence of the channel and spoil mounds, and to a lesser degree from natural bathymetry, and disperses wave energy relatively evenly between the northern and southern sides of the outer harbour. This even distribution of wave energy across the harbour means that wave induced currents do not significantly affect the horizontal circulation patterns within the harbour.

On the southern side of the harbour transport of sand sized material is bidirectional, although predominantly up-harbour due to wave induced currents and a flood dominance over ebb flows on that side of the harbour. Coarser sand is eroded from a region extending from opposite the port to Camp Bay, and very fine sand is eroded from the entire southern side between Little Port Cooper and to the west of Quail Island. Coarser sand is accumulating at the harbour entrance and throughout the inner harbour west of the port, while fine sand is accumulating at the entrance and in Governor's Bay, Head of the Bay and Charteris Bay.

Sand transport on the northern side of the outer harbour is toward a depositional zone at the harbour entrance. This results from the ebb tide on the northern side being faster and of longer duration than the flood. Thus the pattern of sand transport throughout the harbour is one of erosion in the centre and accumulation at the head and at the entrance. The total absence of sand in the channel indicates that there is little or no lateral movement of sand sized material in the outer harbour.

Regions of near-bed fluid mud occur in the outer harbour and represent depositional zones. The most concentrated fluid mud regions coincide with rotatory currents at either end of the tidal gyre, where deposition of fine grained silts and clays from slower currents occurs. These two areas are within the channel, near the breakwater and at the harbour entrance. In the long term there is a net transport of fine grained sediment towards the entrance and to the northern side of the outer harbour. This results from the distribution of sediment flux differentials and from the flux gradients within the harbour.

Comparisons of bathymetric charts between 1849 and 1976 showed that in the long term the harbour is in a state of quasi-equilibrium, although there is a slight net depositional gain in sediment volume. The regions at the head of the harbour and at the harbour entrance have remained in a constant phase of deposition since 1849, while the central harbour regions have varied both spatially and temporally between erosional and depositional states. It is this 'internal' redistribution of sediments which provides the main mechanism for maintaining harbour stability, and this is driven by internal harbour dynamics in the form of a tidal gyre and the dynamic trap. The traditional entrance area/tidal prism ratio approach to inlet stability is irrelevant to this type of inlet which possesses only a single mobile boundary at the bed.

It is concluded that the harbour response to artificial alterations to the system occurred as an erosional phase in bed levels between 1849 and 1903. Alterations primarily took the form of the initial dredging programme, but also included the construction of moles at the port. The erosional phase in the harbour removed more than 11,000,000 tonnes of sediment from the bed, although during this period deposition continued at the head of the harbour and at the entrance.

The controlling mechanisms for long term stability have been identified as the tidal gyre and the dynamic trap. These are able to account for both contemporary and historical stability conditions. The tidal gyre is a function of the interaction between tidal flow and the harbour geometry, and as such would have been operating historically as well as at present. The dynamic trap is a function of both current velocity and near-bed suspended sediment concentration. Without the presence of large quantities of dredge spoil as a sediment supply, rapid deposition from the dynamic trap mechanism would not occur as frequently because the transport load capacity of currents would be exceeded less often. Therefore it is inferred that prior to extensive dredging and dumping of spoil, the net gain of sediment would have been equivalent to the input from catchment erosion and sediment transport through the entrance. In effect the harbour dynamics and controls would have been the same historically as they are now, but in terms of sediment supply to the system the harbour would have been less complex.

Under contemporary conditions the presence of large quantities of dredge spoil causes near-bed suspended sediment concentrations to be high. Transport of fine grained material occurs along positive flux gradients and deposition occurs between two locations where there is a negative flux gradient. The maximum deposition occurs near the zone of maximum transport load capacity, which usually coincides with the region of highest flow velocity. The distribution of sediment flux differentials around the harbour effectively prevents the loss of spoil from the harbour, and induces maximum deposition on the northern side of the channel in the outer harbour, and in the harbour entrance. The tidal gyre also prevents the loss of spoil out of the harbour, and augments the entrance deposition of sediments.

Spoil mounds at dump sites are maintained at a 'maximum capacity' level which is a function of the transport load capacity of the currents at a site, and of the dynamic trap model. All spoil dumped in excess of the dump site capacity is eroded and transported elsewhere within the harbour. Because of flux gradients and the tidal gyre, it is inferred that spoil lost from dump sites is recirculated back to the channel. The present conditions of dump site capacities mean that virtually all the spoil now dumped is eroded and recirculated. Therefore stability is being maintained by the internal redistribution of sediments <u>within</u> the harbour. Channel siltation rates remain approximately equal to the quantities dredged, and the long term stability or net depositional gain to bed levels is equivalent to the natural sediment inputs to the harbour from sources such as catchment erosion.

The second general area of findings arising from the study concerns the classification of inlets, and principles pertaining to the categorization of inlet types. Throughout the thesis a number of characteristics have been identified as distinguishing Lyttelton Harbour from other inlets which have been discussed in the literature. Negligible freshwater input, very fine mud sediments, exposure to ocean swell, minimal littoral drift, lateral grain size contours, and channel siltation rates far in excess of the natural sediment inputs, all combine to differentiate Lyttelton from existing models of inlets.

Aspects of the harbour such as its geological origin and its lateral circulation pattern are similar to existing classification categories, in particular that of well mixed estuaries. The primary difference between the two types of inlets is that Lyttelton lacks a marked longitudinal salinity gradient, although in fact this gradient has little influence on the processes which operate in well mixed estuaries.

Thus the processes and concepts described in this study for Lyttelton Harbour are seen to be applicable to other inlet categories, and are more pertinent to some other inlets in terms of the processes which control them than are the existing concepts and criteria which classifications are based on.

Two main factors are important to the dynamics and description of Lyttelton. Firstly, the main processes operating are tidal currents and these are more significant than any other forms of current which may be operating. Secondly, the rigid rock walls around the harbour confine and limit the processes in a lateral direction and the solid boundary geometry strongly influences circulation patterns. Unlike inlets which have unconsolidated boundaries and entrances, the bed in Lyttelton Harbour is the only boundary which can respond to equilibrium changes. The dynamics of Lyttelton are permanently controlled from within the harbour by the lateral limits imposed by the boundaries. In inlets with unconsolidated boundaries, the inlet and the processes are mutually controlled and regulated by covariation.

Therefore, Lyttelton Harbour has been classified as a structurally controlled tidal inlet. It is inferred from this study and from examination of the literature that well mixed estuaries with hard rock boundaries might be included in this classification because they are tidally dominated inlets with boundary controls. In classifying an inlet as 'structurally controlled', five parameters have been identified from the study as being important for assessing sedimentation patterns and processes in this type of inlet. They are; a dimensionless ratio, D_E/W which reflects process responses to the inlet geometry; the inlet geometry; bed sediment grain size; the presence of unconsolidated features at the inlet entrance; and the magnitude of the sediment supply to the harbour and the form it takes.

The third area to which the study findings contribute is that of dynamic geomorphology. Specifically these findings concern fine grained sediment transport and deposition and have been summarized in a conceptual model, the Dynamic Trap. The principle behind the dynamic trap is the movement of fine sediments with respect to flux gradients between any two locations within the harbour. It has been argued that since sediment transport occurs as the current velocity to some power, sediment flux will decrease rapidly between two high velocity regions where there is a small decrease in current velocity between one location and the next in the direction of flow. Fine sediment will move from regions of low sediment flux to regions of high flux where the transport load capacity of currents will be greatest. Under conditions of high sediment load, any subsequent decrease in flux in the direction of flow will cause rapid sediment deposition since the transport load capacity of the current will be exceeded. Because the current velocity, sediment transport relationship is a power function, the maximum change in flux will generally occur at the point where the current velocity begins to decrease. Therefore maximum fine sediment deposition will occur predominantly at or near regions of high current velocities rather than in quiet, low velocity areas.

In Lyttelton Harbour, the high sediment supply from dredge spoil dumping causes high rates of fine sediment deposition in the areas of increasing flux gradients where the dynamic trap operates. The flux gradients which exist under contemporary conditions mean that sediment cannot readily escape through the entrance. The principle of the dynamic trap means that sediment deposition is maximised, and occurs most readily under sediment oversupply conditions. Given the flux gradients and the location of dumping grounds, this results in mud being deposited within the entrance and along the northern side. Increasing flux gradients across the harbour from south to north cause the long term lateral movement of fines across the harbour, and this results in a lateral gradation of grain size contours which is normal to the main flow paths rather than parallel to them.

The dynamic trap provides an explanation for both the sedimentary and stability characteristics of Lyttelton Harbour. However, more importantly, the model is applicable to other environments where fine sediment is being transported by currents, given a satisfactory sediment supply. Furthermore it is applicable irrespective of the lateral boundary conditions because the system provides its own boundaries in the form of flux gradients, which are dependent on the energy conditions surrounding the dynamic trap zone.

8.1 STUDY EVALUATION AND SUGGESTIONS FOR FURTHER RESEARCH

The aims of the thesis have been achieved, and the proposed research questions have been answered. However, two points, concerning sediment sources and historical stability, have been explained less satisfactorily than was originally desired. Firstly, the potential sediment sources for channel siltation have all been identified, but the contribution by sediment entering the harbour from Pegasus Bay could neither be verified nor determined. The determination of sediment transport and transport paths was difficult because of the unavailability of a satisfactory technique for tracing the fine material. However the data collated have established that dredged spoil is recycled relatively rapidly and is the immediate, and by far the most substantial sediment supply to the channel. Thus the main source has been identified.

Secondly, in terms of the historical stability of the harbour, the magnitude of changes might be queried because of possible errors in chart datums and sounding techniques. In fact the magnitude of change shown is relatively small, with the loss of over 11,000,000 tonnes between 1849 and 1903 representing an average vertical change in bed level throughout the entire harbour of only 15.6 cm, or 2.9 $mm.yr^{-1}$. Of more significance is the demonstration of long term quasi-equilibrium within the harbour. Considering the change over time from a natural state to one where up to 1,000,000 tonnes or more of spoil is available annually for redistribution within the harbour, the maintenance of stability is an interesting factor in the harbour dynamics.

In terms of the original aims and objectives of the study, the Dynamic Trap model has provided a major step toward an explanation of how Lyttelton Harbour operates. Perhaps more significant though, are the wider applications of the model that seem possible in geomorphology. Sediment sinks in geomorphology are generally described in terms of physical boundaries of some sort, and in terms of low or declining current speeds. The dynamic trap offers the notions that, given an available sediment supply of sufficient magnitude, sediment sinks can be bounded by energy "walls", or by dynamic boundaries in the form of flux gradients; can occur in current regimes having both high competence and high capacity; and exist in areas where there are no physical boundaries to the sink zone.

In the light of these foregoing comments, two general areas require further research. They are structurally controlled tidal inlets, and the dynamic trap. In the former case the mechanics of interactions between processes and inlet geometry require further study. For example, the precise cause of the tidal gyre in Lyttelton Harbour is not known, although the excedence of a critical velocity was proposed. Considerably more work is required at a local level, on the mechanisms of tidal variability in Lyttelton Harbour. The variable duration times of flood and ebb tides appears to be a factor in the development and duration of the gyre and of tidal velocities, both of which may affect annual variations in channel siltation rates. At an applied level, it would also be interesting to examine the response of the harbour system to dredge spoil being removed from the harbour and dumped at sea. In terms of the dynamic trap principles and the 'internal stability' concept, the harbour response to the presence of the channel with only a minimal sediment supply requires examination.

At a broader scale the classification of Lyttelton Harbour and the limited set of principles which apply to it need to be applied to other inlets. This has been done in a small way with Wellington Harbour but insufficient data were available to enable a meaningful comparison. In particular, the D_E/W ratio needs to be evaluated for other harbours to assess, and refine, the principles behind the structural control concept. The D_E/W ratio reflects a 'positional' control on internal dynamics within the rigid geometry of a structurally controlled tidal inlet, and its wider application is required to determine its usefulness as a parameter for inlet classification and for predicting the spatial distribution of processes within inlets.

Finally, the mechanisms of fine grained sediment transport and deposition require further study in the light of concepts derived in this study. The dynamic trap has been proposed as a model for fine sediment deposition, and has been examined under conditions of a large sediment supply. To refine the model, further evaluation is required of the precise mechanisms of fluid mud transport, and to determine whether in fact regions of fluid mud represent the depositional end point of the model. Transport along flux gradients and the resulting deposition, or absence of deposition in a dynamic trap region needs to be examined under conditions of low suspended sediment concentrations. These conditions would have prevailed in Lyttelton Harbour prior to the commencement of dredging operations. In particular, the Dynamic Trap model should be applied to a wide range of coastal environments apart from inlets since, by definition, its 'energy boundaries' are applicable to all coastal regions where tidal currents are the predominant process.

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APPENDIX 1

SUMMARY OF FOLK PARAMETERS FOR LYTTELTON SEDIMENTS

Sample No.	Standard Percentiles 5	16	25	50	75	84	95	Folk Parameters Mean Size	Sorting	Skewness	Kurtosis
1	+4.38	+4.50	+4.94	+6.30	+8.15	+9.60	+12.61	+6.80	+2.52	+0.37	+1.05
2	+3.62	+3.89	+3.98	+4.69	+6.70	+8.00	+13.89	+5.53	+2.58	+0.60	+1.55
3	-0.01	+3.81	+3.90	+4.34	+5.65	+7.03	+ 9.90	+5.06	+2.31	+0.27	+2.32
4	+3.67	+3.83	+3.91	+4.21	+5.52	+6.45	+ 9.65	+4.83	+1.56	+0.61	+1.52
5	+2.56	+3.32	+3.52	+3.81	+4.07	+4.60	+ 8.49	+3.91	+1.22	+0.34	+4.42
6	+3.49	+3.75	+3.84	+4.09	+6.02	+8.01	+12.10	+5.28	+2.37	+0.72	+1.62
7	-0.70	+1.25	+3.81	+4.76	+6.99	+8.09	+10.22	+4.70	+3.36	-0.01	+1.41
8	+4.37	+4.49	+4.70	+5.84	+7.50	+9.29	+13.42	+6.54	+2.57	+0.49	+1.32
9	+3.43	+3.75	+3.83	+4.03	+5.10	+6.42	+10.40	+4.73	+1.72	+0.65	+2.25
10	+3.61	+3.84	+3.95	+4.73	+6.70	+7.50	+ 9.30	+5.36	+1.78	+0.47	+0.85
11	+3.57	+3.81	+3.92	+5.04	+7.19	+8.68	+11.84	+5.84	+2.47	+0.50	+1.04
12	+4.32	+4.43	+5.30	+6.61	+8.19	+9.20	+11.31	+6.75	+2.25	+0.20	+0.99
13	+3.51	+3.81	+3.96	+5.31	+7.35	+8.64	+12.11	+5.92	+2.51	+0.43	+1.04
14	+3.41	+3.68	+3.80	+4.59	+7.08	+8.25	+11.32	+5.51	+2.34	+0.57	+0.99
15	+3.31	+3.57	+3.69	+3.96	+5.60	+6.80	+ 9.83	+4.78	+1.80	+0.64	+1.40
16	+4.43	+5.14	+5.80	+7.00	+8.69	+9.58	+11.41	+7.24	+2.17	+0.18	+0.99
17	+3.72	+3.90	+3.99	+5.65	+7.59	+8.91	+11.80	+6.15	+2.48	+0.37	+0.92
18	+3.71	+3.88	+3.94	+4.69	+7.12	+8.71	+12.71	+5.76	+2.57	+0.63	+1.16
19	+3.71	+3.90	+3.98	+5.00	+7.20	+8.30	+10.92	+5.73	+2.19	+0.49	+0.92

Appendix 1 (Continued)

20	+3.53	+3.79	+3.89	+4.32	+6.66	+7.63	+ 9.85	+5.25	+1.92	+0.62	+0.94
21	+3.54	+3.79	+3.89	+4.44	+6.80	+7.72	+10.95	+5.32	+2.11	+0.60	+1.04
22	+4.50	+5.10	+5.80	+7.04	+8.70	+9.42	+11.00	+7.19	+2.06	+0.14	+0.92
23	+3.61	+3.85	+3.94	+4.70	+7.35	+8.33	+10.81	+5.63	+2.21	+0.57	+0.87
24	+3.77	+4.18	+5.50	+7.17	+8.80	+9.53	+11.08	+6.96	+2.45	-0.01	+0.91
25	+4.39	+4.51	+5.35	+6.89	+8.50	+9.39	+11.20	+6.93	+2.25	+0.14	+0.89
26	+3.25	+3.50	+3.63	+3.98	+6.16	+7.35	+12.00	+4.94	+2.29	+0.67	+1.42
27	+4.42	+5.46	+6.02	+7.12	+8.59	+9.21	+10.57	+7.26	+1.87	+0.09	+0.98
28	+3.51	+3.73	+3.86	+4.70	+7.12	+8.70	+12.33	+5.71	+2.58	+0.59	+1.11
29	+4.49	+5.40	+6.11	+7.25	+8.72	+9.40	+10.89	+7.35	+1.97	+0.09	+1.00
30	+3.15	+3.40	+3.53	+3.85	+5.39	+6.91	+10.15	+4.72	+1.94	+0.65	+1.54
31	+4.81	+5.70	+6.20	+7.29	+8.86	+9.50	+10.89	+7.50	+1.87	+0.14	+0.94
32	+3.28	+3.52	+3.68	+4.23	+6.95	+8.31	+12.60	+5.35	+2.61	+0.66	+1.17
33	+3.17	+3.54	+3.74	+4.00	+5.70	+6.80	+11.21	+4.78	+2.03	+0.63	+1.68
34	+5.00	+6.13	+6.50	+7.52	+8.90	+9.51	+10.80	+7.72	+1.72	+0.11	+0.99
35	-2.20	+0.10	+2.15	+3.87	+7.10	+7.85	+ 9.50	+3.94	+3.71	-0.01	+0.97
36	+3.19	+3.46	+3.59	+3.90	+5.96	+7.11	+10.10	+4.82	+1.96	+0.65	+1.19
37	+3.28	+3.57	+3.76	+4.73	+7.33	+8.30	+10.80	+5.53	+2.32	+0.49	+0.86
38	+5.04	+6.09	+6.46	+7.41	+8.70	+9.21	+10.31	+7.57	+1.58	+0.09	+0.96
39	+3.09	+3.40	+3.57	+3.91	+4.60	+6.40	+ 8.04	+4.57	+1.50	+0.54	+1.97
40	+3.37	+3.71	+3.82	+4.10	+4.91	+6.06	+ 9.20	+4.62	+1.47	+0.56	+2.19
41	+0.16	+1.88	+2.38	+3.24	+6.50	+7.46	+ 9.13	+4.19	+2.75	+0.38	+0.89
42	+3.12	+3.36	+3.47	+3.71	+5.09	+6.73	+ 8.59	+4.60	+1.67	+0.66	+1.38
43	-1.75	+3.67	+3.98	+6.15	+7.65	+8.81	+11.27	+6.21	+3.26	-0.09	+1.45

Appendix 1 (Continued)

44	+4.50	+5.57	+6.12	+7.12	+8.68	+9.57	+11.40	+7.42	+2.05	+0.19	+1.10
45	+3.41	+3.75	+3.88	+5.19	+7.39	+8.43	+11.05	+5.79	+2.33	+0.40	+0.89
46	+4.51	+5.80	+6.22	+7.27	+8.71	+9.46	+11.00	+7.51	+1.90	+0.13	+1.07
47	+3.80	+5.00	+5.65	+6.90	+8.77	+9.80	+11.99	+7.23	+2.44	+0.19	+1.08
48	+3.01	+3.29	+3.37	+3.55	+3.80	+4.07	+ 4.61	+3.64	+0.44	+0.22	+1.52
49	+4.47	+5.41	+6.01	+7.01	+8.60	+9.50	+11.35	+7.31	+2.06	+0.20	+1.09
50	+4.33	+4.44	+5.25	+6.84	+8.43	+9.20	+10.81	+6.83	+2.17	+0.11	+0.84
51	+4.61	+5.91	+6.38	+7.36	+8.65	+9.26	+10.54	+7.51	+1.74	+0.07	+1.07
52	+3.21	+3.66	+3.91	+5.96	+7.49	+8.49	+11.00	+6.04	+2.39	+0.16	+0.89
53	+3.12	+3.36	+3.36	+3.72	+4.19	+5.84	+ 9.00	+4.31	+1.51	+0.61	+2.90
54	+3.06	+3.47	+3.72	+5.36	+6.91	+7.84	+10.99	+5.56	+2.29	+0.26	+1.02
55	+4.52	+5.68	+6.17	+7.16	+8.80	+9.71	+11.69	+7.52	+2.09	+0.21	+1.12
56	+4.50	+5.62	+6.08	+7.06	+8.60	+9.49	+11.33	+7.39	+2.00	+0.20	+1.11
57 a	+2.94	+3.50	+3.59	+3.80	+3.99	+4.20	+ 7.16	+3.83	+0.81	+0.32	+4.32
58	+3.43	+3.70	+3.80	+4.12	+6.32	+7.40	+ 9.85	+5.07	+1.90	+0.65	+1.04
59	+3.79	+4.11	+4.69	+5.90	+7.29	+8.40	+11.11	+6.14	+2.18	+0.27	+1.15
60	+4.42	+5.03	+5.59	+6.60	+7.99	+8.91	+10.95	+6.85	+1.96	+0.22	+1.12
61	+4.45	+5.39	+5.80	+6.79	+8.41	+9.61	+12.14	+7.26	+2.22	+0.30	+1.21
62	+3.66	+3.99	+4.50	+6.36	+7.97	+9.02	+11.37	+6.46	+2.43	+0.17	+0.91
63	+3.38	+3.61	+3.71	+4.50	+6.86	+8.70	+14.30	+5.60	+2.93	+0.64	+1.42
64	+5.28	+6.08	+6.39	+7.30	+8.81	+9.41	+10.70	+7.60	+1.65	+0.20	+0.92
65	+4.48	+5.36	+5.79	+6.63	+7.85	+8.71	+10.60	+6.90	+1.76	+0.22	+1.22
66	+3.64	+4.90	+5.51	+6.65	+8.54	+9.63	+11.98	+7.06	+2.45	+0.22	+1.13
67	+4.40	+4.53	+4.83	+5.88	+7.50	+8.70	+11.38	+6.37	+2.10	+0.40	+1.07
68	+4.59	+5.59	+5.99	+6.70	+8.06	+8.99	+10.90	+7.09	+1.81	+0.26	+1.25

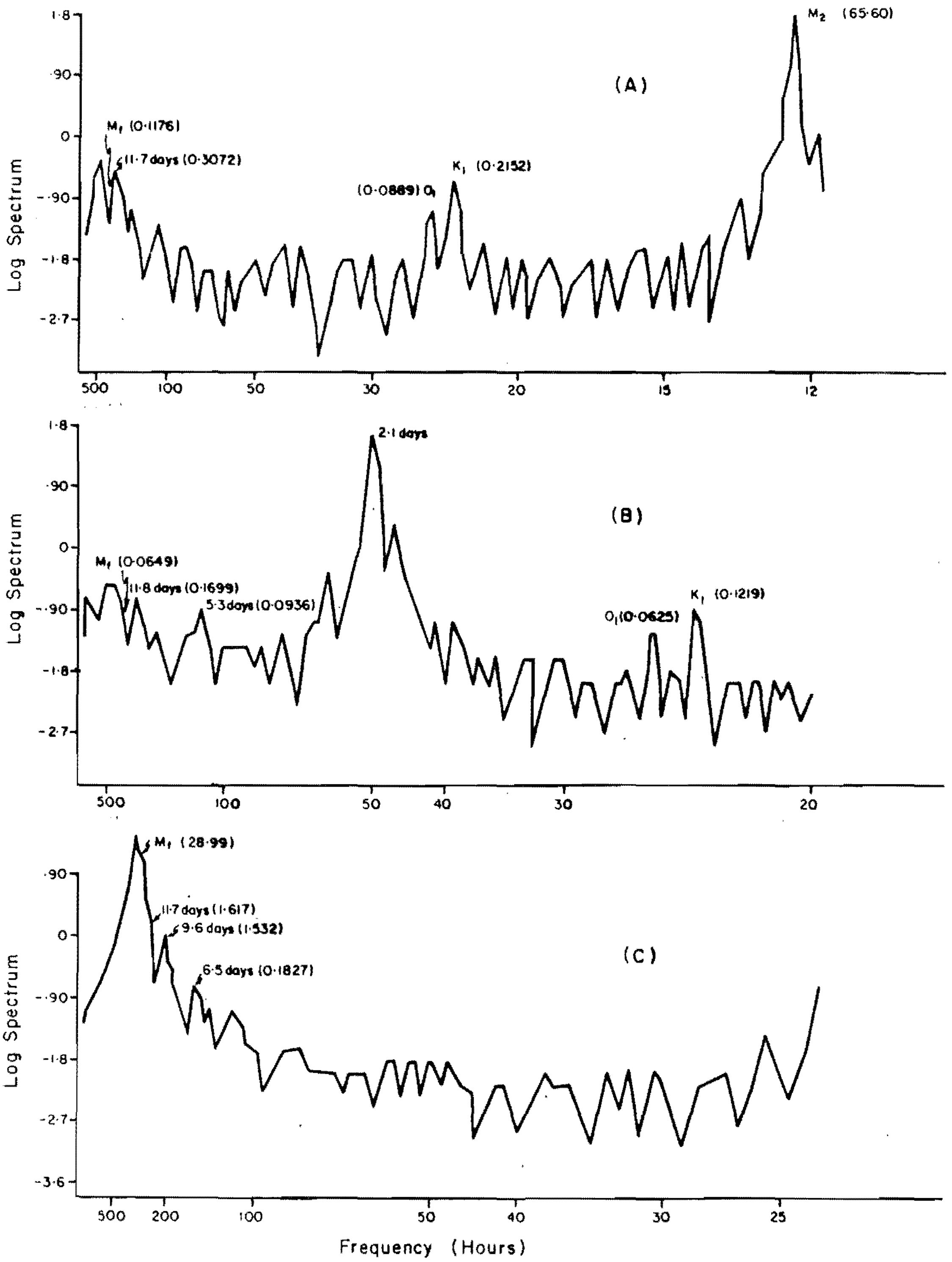
Appendix 1 (Continued)

69	+4.52	+5.36	+5.81	+6.77	+8.50	+9.80	+12.51	+7.31	+2.32	+0.33	+1.22
70	+3.84	+5.05	+5.60	+6.70	+9.02	+11.00	+15.00	+7.58	+3.18	+0.40	+1.34
71	+4.46	+5.50	+5.99	+6.80	+8.20	+9.00	+10.70	+7.10	+1.82	+0.20	+1.16
72	+4.57	+5.76	+6.11	+6.95	+8.33	+9.20	+11.10	+7.30	+1.85	+0.22	+1.21
73	+4.48	+5.39	+5.79	+6.56	+7.78	+8.61	+10.42	+6.85	+1.70	+0.22	+1.22
74	+5.40	+6.10	+6.40	+7.20	+8.65	+9.57	+11.47	+7.62	+1.79	+0.30	+1.11
75	+5.11	+5.85	+6.22	+7.06	+8.50	+9.39	+11.17	+7.43	+1.80	+0.26	+1.09
77	-3.51	-2.47	-1.90	-0.62	+0.10	+0.39	+ 0.91	-0.90	+1.38	-0.41	+0.91
78	+1.48	+1.77	+1.88	+2.21	+2.60	+2.73	+ 3.10	+2.24	+0.49	+0.07	+0.92
79	-4.28	-4.04	-3.66	-2.00	-0.71	-0.26	+ 0.63	-2.10	+1.69	-0.05	+0.68
80	-0.07	+3.69	+3.94	+4.75	+6.85	+8.29	+11.90	+5.58	+2.96	+0.29	+1.69
81	+4.58	+5.24	+5.75	+7.08	+8.98	+9.70	+11.30	+7.34	+2.13	+0.18	+0.85
84	-3.19	-2.60	-2.05	+1.20	+2.99	+3.26	+ 3.59	+0.62	+2.49	-0.34	+0.55
85	+1.37	+1.98	+2.24	+2.69	+3.01	+3.20	+ 3.59	+2.62	+0.64	-0.14	+1.18

APPENDIX 2

Spectral density curves for tidal data with differing sampling intervals showing relative shifts in peak power densities (shown in brackets).

A. Δt = 6 hrs
B. Δt = 10 hrs
C. Δt = 12 hrs.



APPENDIX 3

Contours of suspended sediment during dye sampling at depth $Z/Z_o = 0.2$. Concentrations in mg/l.